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SPECTRAL PHOTOMETRIC STUDIES.

By D. W. MURPHY.

DETERMINATION BY MEANS OF THE ROTATING SECTOR OF THE RELATION OF SPECTRUM INTENSITY TO THE WIDTH OF THE COLLIMATOR SLIT.

AMONG the different methods of comparing the intensities of two spectra that of Vierordt is the most common. The instrument used, in its simplest form, differs from the ordinary spectrometer only in the arrangement of the collimator slit. When the apparatus is to be used for photometric purposes the collimator slit is replaced by two separate slits located one directly above the other. The width of each slit is measured by means of a micrometer screw, and each in turn may be lighted from either of the sources whose intensities are to be compared.[1] The spectra thus formed are situated one above the other, and are separated by a narrow dark band.

The observations are made by means of an ocular which, being supplied with an adjustable slit, allows all the spectrum to be cut off except that part in which the comparisons are to be made. The two fields are brought to the same intensities by varying the widths of the two parts of the double collimator

[1] When measuring the amount of absorption both spectra are lighted from the same source, and the absorption medium is placed between the light and one of the slits.

slit. From the relations of the slit widths for equal intensities in the different parts of the spectrum, the intensity for different colors is found. According to Vierordt we assume that the intensity of a spectrum so lighted is directly proportional to the width of the collimator slit. When the two spectra are of the same intensity the lights are inversely proportional to their respective slit widths.

We shall investigate under what conditions this principle introduced by Vierordt is correct, both for unilateral and for bilateral slits. We know for both cases that when the width of the slit is doubled, twice the amount of light comes to the field of the observer.

The question which we are then called upon to solve is, does the doubling of the amount of light in this manner double the intensity of every part of the spectrum?

Let us imagine, first, an infinitely narrow slit; the spectrum from such a source may be called a pure spectrum, since any point in it will contain light of but one wave-length. If this slit be moved in a direction perpendicular to the edge of the prism the spectrum will travel in the same direction; and a stationary point, as the light traveled over it, would be illuminated by light of different colors. Next, let us consider a wide slit, and think of its being divided into infinitely narrow ones; we recognize that every part of the spectrum from such a source will consist of lights of different wave-lengths superposed upon each other. Such a spectrum we will call an impure one, and it is with such that we are required to deal in practical measurements.

With a unilateral slit only waves that are either greater or less, depending upon the direction of the opening of the slit, than the fundamental wave, will be superposed upon it. If a bilateral slit is used the extra waves which are brought to a given point, due to the opening of the slit, will be both greater and less than the fundamental wave.

From the above consideration it follows: that with a unilateral slit the law of proportionality holds only when the intensities of the adjacent parts of the spectrum are the same; or,

where the curve of intensity is parallel to the one axis of coördinates. With the bilateral slit the law holds where the curve of intensity is a straight line, and may be true for other curves in the region of inflection points. In the latter case the differentials of the increase in intensities due to the light from the opposite sides of the slit, must be equal and of opposite signs.

According to the measurements of Fraunhofer, Koenig, Brodhun and others, the distribution of intensity in the spectrum of the Sun and other incandescent bodies corresponds approximately to the curve shown in Fig. 1.

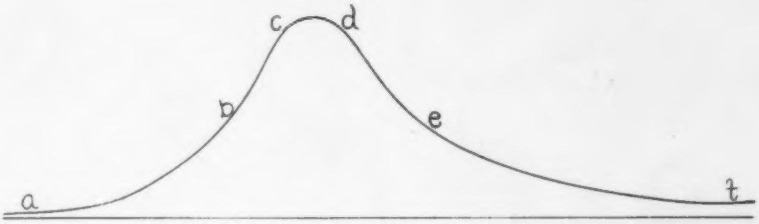

FIG. 1.

The abscissae represent the wave-lengths, and the ordinates the corresponding intensities. From this curve it follows that the unilateral slit is to be used only in those parts of the spectrum where the curve of intensity is parallel to the axis. This is true for only a small part of the spectrum in the region *cd*. The bilateral slit, on the other hand, will give true results not only at *cd*, but in the vicinity of the two points *b* and *e*. When the curve is convex to the axis, as at *ab* and *ef*, the increase in intensity must be more rapid than the increase in the slit width. If the curve is concave to the axis, as at *be*, the increase in intensity is less rapid than that of the slit width.

In order to prove the correctness of these inferences, and to determine the magnitude of the deviation from the law of proportionality, the following observations were made.

Method of observation and apparatus used.—The photometer measurements were made with the Lummer-Brodhun spectral

photometer, a complete description of which may be found in the *Zeitschrift für Instrumentenkunde* for April 1892. This instrument differs in two respects from the spectrometers of Vierordt and others. First, it is supplied with two collimator tubes, *C* and *C'*, placed perpendicular to each other (see Fig. 2); and, second, the observations are made, not by means of an ocular, but by bringing the eye directly before the slit *o*. The plane

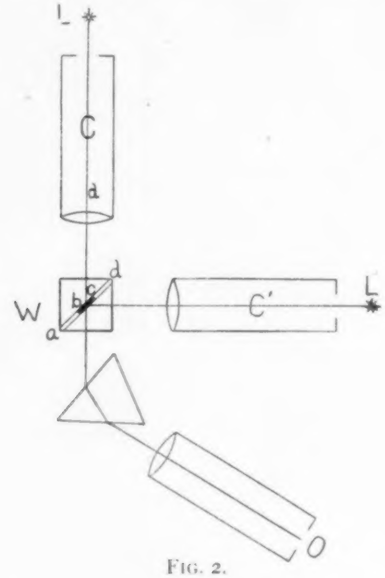

FIG. 2.

ad, which is the hypotenuse of the photometer cube *W*, passes through the axis of the instrument. The field *ab*, *cd* is lighted from the source *L'*, and the field *bc*, from *L*.

The superiority of this instrument over the Vierordt and other similar spectral photometers, lies in the greater accuracy of the photometric comparisons. The fields to be compared are not separated by a dark band, but the boundary is absolutely sharp, and disappears altogether when equal intensity is obtained. The instrument allows not only this principle of likeness, but the principle of contrast[1] as well. Concerning this latter method it

[1] *Zeitschrift für Instrumentenkunde*, February 1892.

may be remarked, that the deviations in the results obtained by it are only one-eighth as great as in those obtained by the ordinary photometers.

In order to test the law of proportionality by means of the variable slit, each collimator of the spectral photometer was provided with bilateral slits. Only the one on C' was used for a comparison slit, as the weakening of the light from L was done by means of a rotating sector placed before the collimator C. According to the careful measurements made by Lummer and Brodhun with the rotating sector of the Physikalische Technischen Reichsanstalt, this method of measuring the increase or decrease of light intensity is accurate to a small fraction of 1 per cent.

The sector was driven by means of a small electric motor, and when rotated at a sufficient speed the field was perfectly clear and free from flickering; any increase in the speed beyond a certain limit gave no change whatever in the results. During the investigations the sector openings were each set at 90°, so that while in rotation the light was decreased one-half.

Various kinds of light sources were tried, but all except the incandescent electric lamp were either too weak or too inconstant to give satisfactory results. The lamps used had an intensity of about 50 candle power each, and were connected in series on the circuit of a storage battery. In order that the illumination of the two slits might be the same in all parts they were covered with milk glass plates. The plane of the lamp fiber was in each case parallel to the glass plates, and the two fibers were at equal distances from the center of the collimator slit.

The positions of the lamps were made secure by their being firmly fastened to T shaped bars, which were screwed to the base of the spectral photometer.

Before beginning the investigation some preliminary experiments were made to determine if the milk glass plates were homogeneous for the entire area to be used. To this end the slits of the collimators were made of equal widths, but both

quite narrow. With equal intensity of fields established in this way the plates were moved so that the different parts were brought over the slit. No change due to this movement, however, could be observed, and the plates were considered homogeneous in so far as their power of transmission was concerned. There was still one other possible source of error that must be investigated. The two lamp fibers were not at equal distances from all parts of the glass plates, and it was necessary to know whether this change in distance affected the uniformity of the illumination for areas as great as were to be used. Computations on this showed that for areas 1^{cm} wide the variation was not greater than 1 per cent. As the areas to be used were but little greater than 1^{mm} wide any error due to this cause was negligible.

The slit was also subjected to a special test, and by means of a micrometer microscope its widths for different readings of the slit's micrometer screw were noted. To avoid dead motion in the screw it was always turned in the same direction in making the settings for photometric equality. From readings on the width of the slit up to 2^{cm} the reading of its zero point was computed; this was to avoid any change due to tension which might be brought in were the slit to be entirely closed.

The method of taking the readings was, in principle, very simple. The two collimator slits were set at the same widths and the lamps adjusted until photometric equality was roughly obtained. The exact adjustment was then made by means of the slit of C'. A series of readings on the width of this slit for equal intensities of fields was then taken. This was for the total light from L. The sector was next started, and a second series of readings on the slit, for equal intensities, was taken. The light from L was in this case of one-half its former intensity. To check any error due to a change in the relative intensities of the two sources the sector was stopped and a second series of readings for the total light from L was taken.

In this way measurements were made for the different colors. The position of the observing telescope for any desired color

was found by means of a mirror attached to the axis on which the telescope turned. This mirror reflected the image of a fixed scale, whose readings for the different wave-lengths had been previously determined.

Four independent series of measurements for the entire length of the spectrum were made. The widths of the slit ranged from approximately $0.^{mm}5$ to $1.^{mm}25$

When the principle of likeness in the photometer was used, the mean of ten readings on the width of the slit was taken. With the contrast principle the agreement was so very close that the number was reduced to five.

Results.—The numerical results are given in Tables I to IV inclusive. The wave-length of the light used is given in column 1. g is the slit width without the sector, and $2\ b$ is twice the slit width when the sector was used. These values are in terms of the divisions of the drum of the micrometer screw ($80^{\,div} = 1^{mm}$). δ is the percentage of difference between g and $2\ b$.

TABLE I.

λ	g	$2\ b$	δ	λ	g	$2\ b$	δ
480	52.6	53.4	−1.5	600	53.5	51.8	+3.3
500	54.0	53.6	+0.7	620	52.8	51.4	+2.7
520	54.2	53.6	+1.1	640	52.9	51.4	+2.9
540	54.5	52.4	+4.0	660	52.6	51.8	+1.5
560	54.4	52.8	+3.0	680	51.7	52.8	−2.1
580	53.9	52.4	+2.8				

TABLE II.

λ	g	$2\ b$	δ	λ	g	$2\ b$	δ
470	56.3	56.8	−0.9	610	63.3	61.4	+3.0
490	60.6	60.2	+0.6	630	63.4	61.6	+2.8
510	60.3	59.2	+1.8	650	63.9	62.4	+2.5
530	61.1	59.6	+2.5	670	64.1	64.2	−0.2
550	61.9	60.4	+2.5	690	64.4	65.2	−1.2
570	62.2	61.2	+1.6	700	64.3	65.4	−1.7
590	63.1	60.8	+3.8				

TABLE III.

λ	g	2b	δ	λ	g	2b	δ
480	68.1	68.6	—0.7	600	72.9	70.6	+3.3
500	69.7	69.2	+0.7	620	73.0	71.0	+2.8
530	70.3	69.4	+1.3	640	73.5	71.0	+3.0
540	70.8	69.2	+2.3	660	74.4	73.2	+1.4
560	71.7	69.8	+2.7	680	75.3	77.2	—2.5
580	72.5	70.8	+2.4	700	74.8	79.2	—5.5

TABLE IV.

λ	g	2b	δ	λ	g	2b	δ
480	98.5	99.4	—0.9	600	103.3	101.8	+1.5
490	101.1	102.0	—1.9	610	103.3	101.4	+1.9
500	100.8	103.4	—2.5	620	103.3	101.8	+1.5
510	98.4	100.8	—2.4	630	103.2	102.0	+1.3
520	98.8	99.8	—1.0	640	104.3	103.2	+1.1
530	99.7	99.8	—0.1	650	102.9	104.2	—1.2
540	100.2	99.6	+0.6	660	102.3	105.8	—2.4
550	100.6	100.6	±0.0	670	102.8	107.2	—4.1
560	101.1	100 8	+0.3	680	103.2	109.0	—5.3
570	101.8	100.6	+1.2	690	103.9	112.0	—7.2
580	102.2	101.0	+1.2	700	104.3	114.2	—8.7
590	102.9	101.6	+1.3				

These results show, for the light source used, that in the middle part of the spectrum the increase of the spectrum intensity is less than the increase in the slit width, that is, $g - 2b > 0$. At the ends of the spectrum just the opposite is observed. These results agree with those deduced from a consideration of the form of the intensity curve. The amounts of the deviations are different for the different wave-lengths, and, in general, are smaller for blue than for green, yellow, and extreme red. It is further shown, that for a given wave-length the deviation changes with the size of the slit used.

Heretofore the measurements have been made through the entire length of the spectrum with nearly the same width of slit, and each particular series gave the results for that width of slit only. In order to study more fully the change for varying slit widths the experiments were repeated in another form. Particu-

lar colors were examined for different slits, from the smallest to the largest size with which the measurements were possible. In this manner results were obtained for the wave-lengths 540, 590, and 690 $\mu\mu$. In Tables V to VII, inclusive, the results are shown. In these results g, b, and δ have the same significance as in the results previously given.

TABLE V. ($\lambda = 540\mu\mu$.)

g	$2b$	δ	g	$2b$	δ
13.0	14.4	−9.8	68.1	67.0	+1.7
17.7	19.0	−6.8	82.7	81.6	+1.4
27.7	28.2	−1.8	103.3	101.6	+1.7
38.0	37.8	+0.5	123.4	122.0	+1.2
53.2	52.0	+2.3	143.1	140.0	+2.2

TABLE VI. ($\lambda = 590\mu\mu$.)

g	$2b$	δ	g	$2b$	δ
13.1	14.4	−9.0	68.5	67.0	+2.2
18.0	19.0	−5.3	84.3	82.0	+2.9
27.9	28.6	−2.4	104.3	101.8	+2.5
38.6	38.0	+1.6	124.0	120.0	+3.6
53.8	52.2	+3.1	145.9	140.1	+4.1

TABLE VII. ($\lambda = 690\,\mu\mu$.)

g	$2b$	δ	g	$2b$	δ
13.3	14.6	−9.0	69.4	70.2	−1.1
18.1	19.2	−6.0	86.7	88.4	−1.9
28.5	29.0	−1.7	107.2	110.2	−2.7
38.4	38.8	−1.0	126.6	135.0	−6.2
54.4	54.6	−0.4	147.8	159.6	−7.4

These tables show, in the first place, a concordance with the former ones; at least they lead to the same general conclusions. Beyond this they teach, that for slit widths below a certain value, for every wave-length $g - 2b$ becomes < 0; that is, the intensity decreases more rapidly than the width of the slit.

The reason for this is most probably the loss of light by diffraction which occurs with narrow slits, and which causes a loss of light proportionally greater as the slit becomes narrower.

With such narrow slits the accurate determination of the zero point is a matter of much importance, and no doubt small inaccuracies arise from this source. It is not probable, however, that with the method used for the determination of the zero point the error is sufficient to change the general conclusions to be deduced.

The results do not give any general law as to the limit of exactness to be obtained by the Vierordt method of measuring the light intensity. In fact any general law is impossible, since it varies with the relative intensities and the kind of lamps to be compared.

We may conclude, however, that the assumption that the spectrum intensity is proportioned to the width of the slit is not strictly true, and it is to be used with caution; that in the blue and central parts of the spectrum it is in error for slits in the ratio of 1 to 2 as much as 2 or 3 per cent., while in the red this error may become as great as 10 per cent. This shows that this method of measuring light intensity is, in exactness, far behind the present methods of photometric comparisons, at least with such an instrument as the Lummer-Brodhun spectral-photometer. This apparatus gives with the intensity of light used an exactness of adjustment of about 0.3 per cent. Also by means of the rotating sector the same accuracy for decreasing the light is obtained, even when the sector openings are small.

INVESTIGATION OF THE TRUTH OF THE FRESNEL FORMULA FOR THE INTENSITY OF REFLECTED LIGHT, AND THE DEPENDENCE OF THIS INTENSITY ON THE COLOR OF THE LIGHT USED.

Since Fresnel, from a theoretical consideration, gave his celebrated formula for the amount of light reflected from the surface of a transparent medium, the experimental verification of it has been a problem of interest to investigators in optical

science. And of all the methods used, the photometer—the simplest in principle—was applied relatively very late. This is probably due in a large degree to the hitherto inexactness of photometric measurements which, with the small amount of light reflected, gave rise to serious errors.

It is for this reason that Professor Rood,[1] who was the first to investigate the subject, prefers measuring the amount of light transmitted by thin plates of glass, and from these results to compute the reflection at the first surface. Lord Rayleigh,[2] and shortly after him Sir John Conroy[3] were the first to choose the experimentally difficult, but decidedly less objectionable, method of measuring directly the amount of the reflected light. In order to prevent the great loss of light by diffusion which takes place in the ordinary photometers, Rayleigh dispensed with the use of diffusion screens and used only direct reflection from the light source to the eye. He observed from the amount of light reflected from the surface of glass prisms that only those surfaces which had been freshly polished gave results consistent with theory. Conroy measured not only the light reflected, but also that transmitted by glass plates, hoping in this manner to find an explanation for the differences which so often exist between observed and computed results. He concluded that the amount of light reflected from a glass surface varies with the kind of polish to which the surface has been treated.

Even though a sufficient reason for taking up the subject anew might be found in the variations of results heretofore obtained, I had still another purpose in so doing. Rayleigh and Conroy in their investigations used white light, and as a basis for their calculations used the refractive index of the color of greatest intensity. They further used ordinary unpolarized light, while the Fresnel formula is deduced from a consideration of lights polarized in and perpendicular to the plane of incidence. A much more complete test of the formula would, therefore, be

[1] *American Journal of Science*, **50**, 1.

[2] *Proc. R. Soc.*, **41**, 275.

[3] *Phil. Trans.*, Vol. A 1889, p. 245.

obtained by working with light polarized at different angles to the plane of incidence. So far as I know, no investigations had been made on the amount of the reflection for lights of different colors, and no experiments that have been carried on in a purely photometric way, show that the amount of reflection is different for the different wave-lengths of the light used.[1] By means of the linear bolometer, Rubens has investigated the Fresnel formula in the ultra-red part of the spectrum, and has found that the amount of energy reflection varies for different wave-lengths.

In the following I shall show, that with the aid of the Lummer-Brodhun spectral photometer, in connection with a rotating sector for measuring the weakening of the light, and a secondary spectrometer for determining the angle of incidence of the reflected ray, we can measure the amount of reflection for any wave-length and for any desired angle of incidence. By using a Nicol placed in the path of the ray it is possible to extend those measurements to light polarized in any desired plane. The measurements to be made with special care, however, are those which show the relations of the intensities of the different colors in the spectra of the direct and reflected light.

Method of investigation and description of the apparatus.—In Fig. 3 is shown a horizontal cross section of the apparatus giving the arrangement of the different parts. The spectral photometer consists of the tubes C, C' and T, the photometer cube W, and the refracting prism P. C and C' are the collimators

[1] The Fresnel formula,

$$I_r = I_i \tfrac{1}{2}\left[\frac{\sin^2(i-r)}{\sin^2(i+r)} + \frac{\tan^2(i-r)}{\tan^2(i+r)}\right],$$

in which I_r is the amount of light reflected, I_i the incident, i the angle of incidence, and r the angle of refraction. This formula shows that as n (the refractive index) increases, $\sin(i-r)$ becomes larger, and, up to a certain point, where $(i + r = 90°)$, $\sin(i+r)$ becomes smaller. The same is true of the second term. The formula then says that for a given angle of incidence the amount of reflection will be a function of the refractive index, and if this index be increased the amount of reflection will be increased. We can further deduce, that since the change in the amount of reflection is a transcendental function, it will be different for different angles of incidence.

by means of which the light rays from the sources *L* and *L'* are rendered parallel before reaching the photometer *W*. *T* is the observing telescope and is provided with a variable ocular slit *o*. When the apparatus is in adjustment an eye placed before *o* sees the photometer fields lighted from the illuminated slits *s* and *s'*. The light sources used, *L* and *L'*, consisted of incandescent electric lamps of approximately fifty candle power each. The lamps were joined in series to a circuit, and supplied with a

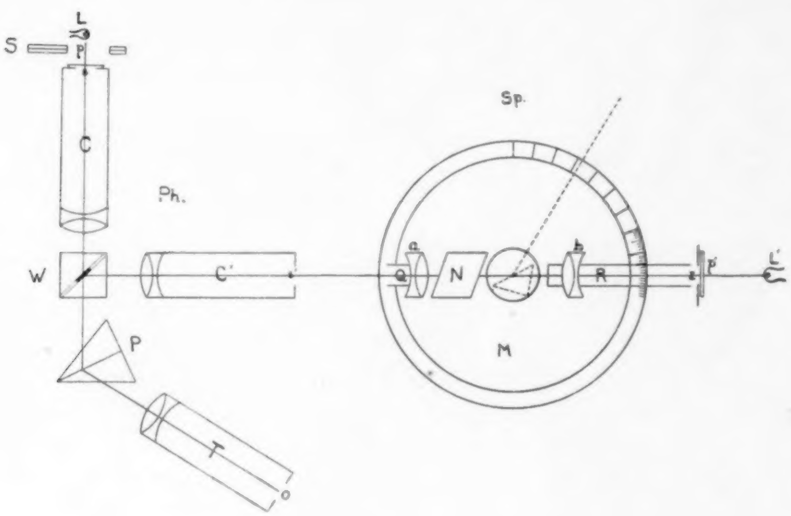

FIG. 3.

current from a storage battery, having an E. M. F. of thirty-two volts. The light source *L* is firmly fastened to an arm of the spectral photometer, and always lights in the same manner the one field of the photometer *W*. The other light source, *L'*, is mounted upon a separate piece of apparatus, *Sp*. This apparatus, which is a form of spectrometer, consists essentially of the circular plate *M* to which are fastened the arms *Q* and *R*. The plate *M*, whose diameter is about 50^{cm}, is turned from a heavy slab of slate, and its edge, being graduated, serves as the

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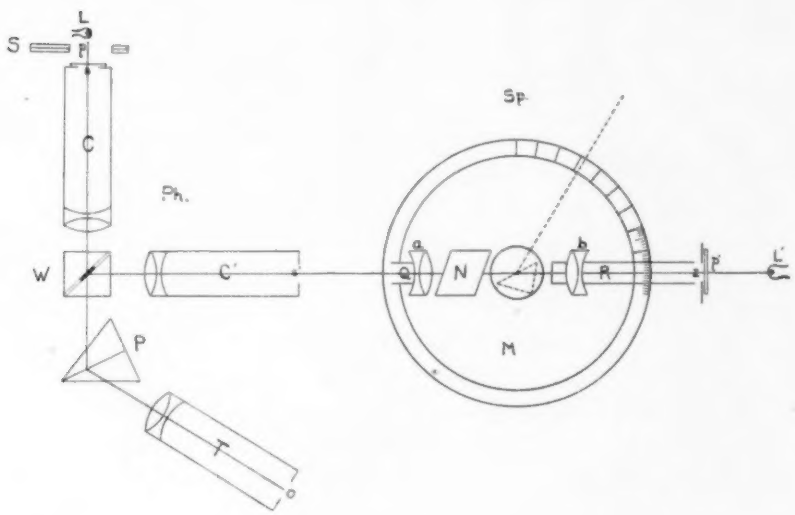

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spectrometer circle. The metal arm R, which carries the lamp L', is so mounted that it turns about an axis through the center of M, and its position is read by means of the graduated circle. The arm Q is firmly fastened, and always retains the same position relative to the spectrometer disk. The lamp L' is enclosed so that the only light emitted from it is through the slit z. The slit z and the collimator slit s are covered with milk glass plates p and p', the purpose of which is to give a more uniform field than could be got from the lamp direct. The lenses a and b are mounted so as to slide along the arms Q and R in the path of the ray. These lenses are so adjusted that the light from z passes in parallel rays from b to a, and is brought to a focus again on the slit s'.

The spectrometer as a whole is so placed that when the arm R is at its zero position, that is, making an angle of 180° with Q, the axis of the spectrometer cuts the straight line passing through the center of W and the slits s' and z. The pencil of light between b and a will then be concentric with the line of collimation of C', and will cut the spectrometer axis at right angles. When viewed with an ocular placed before o the images of s and s' will be seen to exactly coincide, and the color of the two fields will, with this adjustment, be the same for all positions of the observing telescope. In order to compare the intensities of light of any desired wave-length, it is only necessary to turn the telescope T until that color is brought into view.

The surface whose reflecting power is to be measured is placed upon the table of the spectrometer in such a position that it lies in the plane passing through the axis. By rotating the table the reflected light may be made to fall upon s' for all positions of the arm R.

In order to compute by means of the Fresnel formula the amount of the reflected light, one face of a Steinheil prism was used as a reflecting surface. The refractive indices of the prism for the desired wave-lengths had been carefully measured.

The light from the source L was weakened to the same intensity as that of the reflected portion from L' by means of a rotating

sector S placed between L and the slit s. The size of the sector opening could, during rotation, be changed at will from 180° to 0°, and by means of a vernier read to an accuracy of 0°.02. Upon the arm Q, and between the reflecting surface and the lens a, a Nicol prism N could be mounted. By revolving the Nicol in its mountings the light which fell upon s' could be polarized at any desired angle with the plane of incidence.

Dependence of the amount of reflection on the wave-length.—The method of finding the variation in the amount of reflection for different wave-lengths was as follows: The relation of the intensities of the light sources L and L' for two colors, first for the direct and then for the reflected light, was measured. A comparison of these ratios gave the excess of reflection for one color over that of the other.

The method of observation for this is very simple in form. First, the slits s and s' are set at approximately the same widths. With the arm R at its zero position and the sector open to nearly 180°, the lamps are adjusted until the fields are of nearly the same intensity for one color; all other conditions remaining the same, equal intensities are obtained by opening or closing the sector. After a series of ten settings has been made, and readings on the size of the sector opening taken, the observing telescope is turned so as to observe the light of the other wave-length, and a second series of sector readings for equal intensities of this color is taken.

The ratio $\frac{O_\lambda}{O_1}$, of the sector readings for the two colors, which is denoted by I_d, is the relation of the intensities of these colors in the spectrum of the direct light from L'. This relation is in terms of the spectrum from L, which may be considered of unit intensity for every wave-length.

The arm R is next moved from its zero position, and the reflecting surface placed on the table of the spectrometer. In order to bring the photometer fields to the same intensity when using only the reflected portion of the light from L', it would require a very considerable diminution of the sector. Measure-

ments made in this way do not possess the highest degree of accuracy on account of the smallness of the sector opening. To avoid this source of inaccuracy the sector was left at its original size, and the light source L removed until the intensities were approximately equal.

The values of O_λ' and O_l' for the reflected ray were then obtained in the same manner as for the direct ray. The quotient, $\frac{O_\lambda'}{O_l'}$, is denoted by I_r. From a consideration of the above we have $\frac{I_r}{I_d}$ as the relation of the reflection of light of wave-length λ to that of light of wave-length l.

For example, the readings of the half-sector openings for wave-lengths $535\mu\mu$ and $670\mu\mu$, for the direct light were $O_\lambda = 81^\circ.33$ and $O_l = 75^\circ.76$ (λ being considered as wave $535\mu\mu$ and l as wave $670\mu\mu$).

The value of I_d was therefore $\frac{81.33}{75.76} = 1.074$. For the light reflected at incidence angle of 20° the results obtained were $O_\lambda' = 80^\circ.25$ and $O_l' = 73^\circ.35$. From this $I_r = 1.094$ and $\frac{I_r}{I_d} = 1.019$. This shows that for light of wave-length $535\mu\mu$, 1.9 per cent. more light is reflected than for light of wave-length $670\mu\mu$.

TABLE I.

Relations of the amounts of light reflected for $\lambda = 535\mu\mu$ and $670\mu\mu$.

Incidence angle	Observed	Computed
20°	1.019	1.015
40	1.019	1.015
60	1.010	1.008
80	1.003	1.002

The results of these investigations for different incidence angles are given in Table I. The computed values are the ratios of the amounts of reflection taken from the results computed by the Fresnel formula for the corresponding angle of incidence

and for the refractive indices of the glass for wave-lengths $535\mu\mu$ and $670\mu\mu$. [See Table III.]

Character of light reflected from colored plates.—Measurements were made on the intensity of the different colors of the spectrum for lights reflected from different colored glass. For this purpose, glass plates, the reverse side of which had been covered with asphalt black, were used. Red, as well as blue, glasses gave for the blue a stronger reflection than for the red rays, showing that the composition of the reflected light is not changed by the color of the reflecting medium. These results were not compared with theory, since the refractive indices of the plates for different wave-lengths of light could not be readily determined.

Measurement of the amount of light reflected for different colors and at different angles of incidence.—The problem of measuring the absolute amount of light reflected is in theory a very simple one. For its solution it is necessary only to compare the total incident light from L' with the reflected portion. This is done by taking the sector readings for equal intensities of the photometer fields with R at its zero position and at the position of the desired angle of incidence. The comparison of the direct with the reflected light, however, is attended with two experimental difficulties. First, the reflected portion is small, being, for the smaller angle of incidence, only about 4 per cent. of the total incident light. Second, the reflected light, more especially for large angles of incidence, is partly polarized at the reflecting surface. The first condition leads to the measuring of small sector openings, the adjustment and reading of which require especial care to prevent error.

The polarizing of the light at the reflecting surface may lead to another source of error, since in the spectral photometer the refracting prism also produces polarization, and in this case acts as an analyser in destroying the light which has been polarized by reflection. It is for this reason that photometers consisting simply of diffusion screens have in some cases been brought into use for measuring the amount of reflected light.

The error due to polarization may, however, be entirely avoided by placing a polarizer in the path of the ray, between the reflecting surface and the lens *a*. For this purpose a Nicol prism of $45^{mm} \times 45^{mm}$ opening was used. With this arrangement the measurements, for both the direct and the reflected rays, are made for light polarized in one plane whose position is identical with that of the Nicol. In order to compare the results obtained by measurements with those computed from the formula it is necessary to know accurately the polarizing plane of the Nicol. This may be found by computing from the refractive index with the help of the Brewster formula, $\mu = \tan i$, the angle of incidence under which the reflected light is totally polarized. The position of L' is adjusted by means of the movable arm R until the light falls upon the surface at this angle; the Nicol is then turned until the light which reaches the photometer from L' is a minimum. At this position the polarizing plane of the Nicol is perpendicular to the plane of incidence. By means of the graduated circle on the Nicol mounting I was able to bring the polarizing plane to any desired position and to read its position to an accuracy of $5'$.

Method of observation.—After the Nicol had been adjusted the reflecting prism was removed and the arm R placed at its zero position. By means of the rotating sector the photometer fields were brought to the same intensities, and a series of five readings on the size of the sector opening was taken. The arm was then turned to the position for the required angle of incidence, and the prism so placed that the reflected light fell upon the slit s'. Photometric equality was then brought about by closing the sector, and a series of readings on the size of the sector opening was taken. To avoid any error due to a change in the relative intensities of the light sources during the measuring process, the arm R was again placed in its zero position, the prism removed, and a second series of five readings of the sector for direct light was taken.

The ratio of the two sector openings gives the relation of the incident to the reflected light. If we consider the incident light

equal to one hundred, which has been done in the following results, the amount of the reflection is given in terms of per cent. of the incident light.

Measurements were made for light of wave-lengths 535 $\mu\mu$ and 670 $\mu\mu$, and for three positions of the polarizing plane, which were at angles of 0°, 45° and 90° with the plane of incidence.

The results are given in the following tables. *I* is the angle at which the incident light falls upon the reflecting surface. The observed values are the results obtained from a single series of observations, and not the mean of several sets of readings.

The computed results are deduced from the Fresnel formula:

$$I_r = I_i \tfrac{1}{2}\left[\frac{\sin^2(i-r)}{\sin^2(i+r)} + \frac{\tan^2(i-r)}{\tan^2(i+r)}\right].$$

The refractive indices were obtained by direct measurement, and were for wave-lengths 535 $\mu\mu$ and 670 $\mu\mu$ respectively, 1.56462 and 1.55896.

The differences between the observed and computed results are given direct, and are not—owing to the different values of the reflected light—computed in terms of percentage.

These tables show in general a close agreement between the observed and computed results, the differences being in every case but a small percentage of the total incident light, while in many cases they are almost perfectly concordant. The greatest discrepancy exists for light polarized perpendicular to the incidence plane, and in this case for the small angles of incidence.

TABLE II.

Light polarized in the incidence plane.

	$\lambda = 670\ \mu\mu$			$\lambda = 535\ \mu\mu$		
I	Observed	Computed	δ	Observed	Computed	δ
20°	5.60	5.58	+0.02	5.61	5.66	−0.05
40	9.24	8.94	+0.30	9.20	9.06	−0.14
60	19.64	19.64	±0.00	20.19	19.80	+0.39
80	55.73	56.04	−0.31	56.72	56.24	+0.48

TABLE III.

Light polarized at an angle of 45° to the incidence plane.

	$\lambda = 670\ \mu\mu$			$\lambda = 535\ \mu\mu$		
I	Observed	Computed	δ	Observed	Computed	δ
20°	4.80	4.80	±0.00	5.10	4.87	+0.23
40	5.60	5.38	+0.22	5.63	5.46	+0.17
60	9.62	9.87	−0.25	10.12	9.95	−0.17
80	39.07	39.65	−0.56	39.04	39.73	−0.69

TABLE IV.

Light polarized perpendicular to the incidence plane.

	$\lambda = 670\ \mu\mu$			$\lambda = 535\ \mu\mu$		
I	Observed	Computed	δ	Observed	Computed	δ
20°	4.43	4.02	+0.41	4.38	4.08	+0.30
40	2.03	1.82	+0.21	2.00	1.86	−0.14
60	...	0.10	.....	....	0.10	......
80	23.05	23.16	−0.11	22.76	23.22	−0.46

If these many independent observations speak for the correctness of the Fresnel formula, they also give evidence of the exactness of the photometric comparisons, and of the method of measuring by means of the rotating sector despite the small amount of reflected light.

As the measurements for light polarized perpendicular to the plane of incidence could not be repeated, the spectral photometer being in use for other investigations, I am unable to give any explanation of the slightly greater variations between observed and computed results in this particular case. It is not probable that the Fresnel formula fails to give correct results in this particular case, but that the cause for these variations is to be sought for in some other source of inaccuracy.

In Table V I have given the results obtained without using the Nicol at *Q;* this will show the magnitude of the error which may affect results when the polarizer is not used as a ray filter.

TABLE V.

	$\lambda = 670\ \mu\mu$			$\lambda = 535\ \mu\mu$		
I	Observed	Computed	δ	Observed	Computed	δ
20°	4.70	4.80	−0.10	4.74	4.87	−0.13
40	4.60	5.38	−0.78	4.62	5.46	−0.84
60	7.77	9.87	−2.10	7.79	9.95	−2.16
80	34.44	39.65	−5.21	34.41	39.73	−5.32

The calculated values for the reflection of ordinary light are the same as for light polarized at an angle of 45° to the incidence plane. [Compare Table III.]

For small angles of incidence where the polarizing effect is small, the observed and computed results agree to within 2 per cent. When the angles of incidence are large this difference rises to 12 per cent. and over.

In a second work, which I hope to be able to carry out, I shall use the method described above to study the influence which the treatment and character of the surface have on the amount of the reflected light.

In conclusion I wish to express my thanks to the Physikalische Technischen Reichsanstalt for the opportunities granted me for carrying out the above investigations, and to the members of the institution for the many courtesies shown me, especially to Professor Lummer and Dr. Brodhun, to whom I am indebted for much valuable assistance.

Stanford University,
April 1897.

NOTE ON THE CHEMICAL COMPOSITION OF THE MINERAL RUTILE.

By B. HASSELBERG.

IN my researches on the arc-spectrum of titanium I employed, as elsewhere stated[1], instead of the commercial metallic powder, a Norwegian specimen of the mineral rutile, mainly on account of the far greater steadiness of the arc thus formed. According to the hitherto published chemical analyses of this mineral[2], I had no good reason to expect any foreign lines of importance other than those of iron, the more conspicuous of which would be present in any case on account of impurities in the carbons. However, upon examining the arc-spectrum of vanadium obtained from a specimen of this metal presented to Baron Nordenskiöld by Moissan of Paris, I found, to my great surprise, that several of its strongest lines coincided exactly with faint lines in my titanium spectrum, thus indicating a very appreciable percentage of vanadium in the rutile analyzed. This induced me to investigate more closely the spectra of other specimens of the mineral in question, particularly as I had the opportunity to select from among the rich collections of the Royal Mineral Cabinet varieties from different quarters of the world.

In the comparisons I have used only the part of the spectrum included between $\lambda 460$ and $\lambda 427$. This is sufficient, for in this region there is situated one of the most prominent groups of the whole vanadium spectrum, namely the group $\lambda 441-438$, the presence of which in the spectrum of any rutile, even though feeble in intensity, would indicate indubitably the presence of a sensible percentage of the metal. In order to decide definitely concerning the coincidences, the above named part of the vanadium spectrum was photographed upon the same plate with the

[1] *Svenska Vetênsk. Akad. Handl.* Also *Ap. J.*, **5**, 194–198, 1897.

[2] DANA, *Descriptive Mineralogy*, fifth edition. New York, 1883, p. 160.

same region of the spectra of the different rutiles, and on these plates the intensities of the rutile lines corresponding to vanadium were estimated on a scale in which 1 denotes the faintest, and 6 the strongest lines. A + or − after a number indicates the intensity of the line in question to be nearer to this number than to the next; thus 1+ denotes an intensity greater than 1, but not attaining 1.2, and so on. In this way the following table has been constructed, which contains the results of the investigation of twelve rutiles, namely:

Norway:	1.	Rutile from Krageröe.
	2.	" " Langöe.
	3.	" " Lofteshagen.
Sweden:	4.	" " Käringbricka.
Russia:	5.	" " Tachowaja, Ural.
	6.	" " Miask, Orenburg.
Switzerland:	7.	" " Binnenthal, Wallis.
France:	8.	" " Yrieix.
Germany:	9.	" " Freiberg.
Spain:	10.	" " New Castilia.
America:	11.	" " Graves Mountain, Lincoln Co.
	12.	" " Magnet Caves, Arkansas.

From Table A it will be seen that, with one exception, all the rutiles examined contain vanadium in varying proportions. This exception is found in the Anatas from Binnenthal, Canton Wallis, in Switzerland, in the spectrum of which the vanadium lines are almost absolutely wanting. This statement is not invalidated by the greater intensity of the two lines 4444.40 and 4441.90, for these lines belong without doubt to titanium, although they differ so very little in position from the vanadium lines that a separation on my spectrograms is impossible.

On comparing the intensities of the vanadium lines in the different specimens of rutile, the singular fact at once manifests itself that varieties from neighboring lodes contain a very different percentage of the metal. Thus among the Norwegian rutiles the two specimens from Langöe and Lofteshagen contain vanadium in a much larger proportion than the Krageröe rutile, and the same holds good for the two Russian and also for the American rutiles. This peculiarity finds a counterpart in the

TABLE A.

RUTILE FROM

Vanadium λ	I	Krageröe	Langöe	Lofteshagen	Käringbricka	Tachowaja	Miask	Binnenthal	Yrieix	Freiberg	Castilia	Graves Mountain	Arkansas	Remarks
4268.85	3	...	1+	...	1	1	1—	...	tr.	1—	1	1+	tr.	The sign tr.
71.80	3	...	...	...	1	...	...	...	...	...	...	...	...	(trace) indicates
4330.15	3	...	1—	tr.	1	tr.	tr.	...	...	tr.	tr.	1	...	an intensity too
33.00	3	...	1	1	1	1	tr.	...	...	tr.	1—	1.2	...	feeble to be esti-
41.15	3	...	1+	1	1—	1	tr.	...	tr.	1—	1	1.2	tr.	mated
53.05	3.4	1	1+	1+	1.2	1+	tr.	...	tr.	1—	1	1.2	tr.	
79.42	4.5	2	3	2.3	3—	2.3	2—	tr.	2	2	2.3	2.3	2—	
84.95	4.5	2	2.3	2+	2.3	2+	1.2	tr.	2—	2—	2+	2+	1.2	
90.15	4.5	2	2	2	2+	2	1	...	1.2	1.2	2—	2	1+	
95.40	4.5	1	1.2	1.2	2	1.2	tr.	...	1+	1	1+	2—	1	
4400.75	4	1.2	2—	1.2	2	2—	1	1+	1.2	1.2	2—	2—	1+	
06.85	4.5	...	1.2	1.2	2—	1.2	tr.	...	1	1	1+	2—	1	
07.90	4.5	1.2	2—	2—	2	2—	1	tr.	1.2	1.2	2—	2+	1+	
08.40	4	1.2	2—	2—	2	2—	1	...	1.2	1.2	2—	2+	1+	
08.65	4.5	1.2	2—	2—	2	2—	1	...	1.2	1.2	2—	2+	1+	
16.65	3	2	...	...	2	...	...	...	...	...	...	...	...	
38.03	3.4	...	1	1—	1	1	1	...	...	tr.	tr.	1	...	
41.90	3.4	1.2	2—	2—	2—	1.2	1.2	1+	...	1.2	1.2	2—	1	Ti
44.40	3.4	...	2—	2—	1.2	1.2	1.2	1.2	...	1.2	1.2	2—	1	Ti
52.12	4	...	1	1—	...	1—	tr.	tr.	...	tr.	1—	1.2	...	
59.95	4	tr.	1+	1+	1.2	1.2	1—		1—	1	1	1+	1	
60.45	4.5	1	1.2	1.2	2—	2	1		1+	1.2	1.2	2—	1—	
62.55	3.4	tr.			1	1	...		tr.	tr.		1	1	
69.90	3.4	...			1—	1—	tr.		tr.	tr.		1—	1	
4545.62	3.4	...			1.2	1+	1		1	1		1+	1+	[Co
49.85	3	3.4			3.4	3.4	3.4		3.4	3		3.4	3.4	Belongs to Ti,
77.40	4	tr.			1+	1+	1—		tr.	1		1	tr.	
80.55	4	1			1.2	1.2	1		1	1+		1+	1	
86.55	4.5	1			1.2	1.2	1—		1	1+		1+	1	
94.30	4.5	1			1.2	2—	1—		1	1+		1+	1	

case of another component of some rutiles, namely, chromium, of which metal a very notable amount was discovered in the Swedish specimen from Käringbricka as early as 1803,[1] and is now detected in some of the varieties under discussion.

In order to prove that the observed titanium lines are not to be ascribed to an impurity of the carbons, the spectrum of the latter was photographed with that of vanadium before introducing rutile into the arc. Besides the ordinary carbon bands the

[1] DANA, *Mineralogy*, p. 161.

resulting plates show feebly only a few of the most conspicuous iron and calcium lines, but of vanadium not the least trace is seen. The purity of the carbons analyzed is thus to be considered as entirely satisfactory.

While the presence of vanadium in the rutile thus forms a hitherto entirely unknown feature of this mineral, the presence of chromium in the Swedish variety was, as above stated, detected by chemical analysis as early as 1803, and has since then been verified in some other specimens. The present method of research, however, permits of a much easier decision in this respect on account of the occurrence of one of the strongest groups of the whole spectrum of chromium, viz., λ4289.9, 4274.9, 4254.5 just within the part here photographed. It is not very difficult to find them out among the crowd of titanium lines on the photographs, and from their estimated intensities, to form at least an approximate idea of the greater or less quantity of chromium contained in the specimens examined. In the following table the results of these comparisons are given :

TABLE B.

RUTILE FROM

Chromium λ	I	Krageröe	Langöe	Lofteshagen	Käringbricka	Tachowaja	Miask	Binnenthal	Yrieix	Freiberg	Castilia	Graves Mountain	Arkansas
4254.49	6	tr.	3	3	2.3	3	tr.	...	2.3	2.3	2.3	2.3	...
74.91	6	...	2.3	2.3	2–	2+	...	...	2	2	2	2+	...
89.87	6	...	2	2	2–	2	...	...	1.2	2–	2–	2	...

It will be seen that in different rutiles the chromium lines show differences of intensity, fully justifying the conclusion of a corresponding disparity in the amounts of the metal. Thus, while the Anatas and also the Arkansas rutile are absolutely free from chromium, and in the rutiles from Krageröe and Miask only a feeble trace is present, the other specimens contain a very considerable percentage of this metal. But the

most peculiar feature in this respect appears upon comparing chromium with vanadium. It is thus found that in those varieties of rutile which contain vanadium in any very appreciable amount, chromium is also present, while a small percentage of the former metal is accompanied by a corresponding scarcity or even complete absence of the latter.

In conclusion it should be remarked that in the case of the Norwegian rutile from Langöe the preceding results have been completely confirmed by ordinary chemical analyses kindly undertaken by Baron Nordenskiöld. It is thus evident that the accepted chemical analyses of the present mineral by no means possess the completeness or accuracy which the usual chemical methods are capable of giving.

STOCKHOLM ACADEMY OF SCIENCES,
April 1897.

TABLES OF THE PRACTICAL RESOLVING POWER OF SPECTROSCOPES.

By F. L. O. Wadsworth.

In the article "On the Conditions of Maximum Efficiency in the Use of the Spectrograph" published in a recent number of this Journal[1] I have pointed out that the commonly accepted formula for purity is incorrect and have derived (from theoretical considerations verified by experimental results) three new formulæ for the following cases which cover, I believe, all those met with in theory or practice:

1. The resolving power p (theoretical) for a wide slit and monochromatic radiations.

2. The resolving power R (limiting) for an infinitely narrow slit but for lines of finite width, $\Delta\lambda$.

3. The resolving power P (practical) for a wide slit and non-monochromatic radiations ranging for each line over a small value $\Delta\lambda$ as in (2).

The formulæ obtained were

$$p = \frac{\lambda}{s\psi + \dfrac{\lambda}{2s\psi + \lambda}\lambda} r \qquad (1)$$

$$R = \frac{\lambda}{\frac{4}{7} r\Delta\lambda + \dfrac{\lambda}{r\Delta\lambda + \lambda}\lambda} r \qquad (2)$$

$$P = \frac{\lambda}{s\psi + \dfrac{\lambda\left(\frac{r}{R}\right)}{2s\psi + \lambda\left(\frac{r}{R}\right)}\left(\frac{r}{R}\right)} r \qquad (3)$$

In these formulæ s is the width (linear) of the slit; ψ the the angular magnitude of the collimator as viewed from the slit; and r the theoretical resolution of the instrument for infinitely narrow slit and infinitely narrow spectral lines. The value

[1] "The Modern Spectroscope," *Ap. J.*, 3, 321, May 1896.

of r (which was first derived for both prisms and gratings by Rayleigh) may be most simply expressed as I have previously shown[1] as a product of the linear aperture, a, times the angular dispersion, D, divided by a constant m which varies from unity (for a rectangular aperture) to about 1.1 (for a circular aperture), or

$$r = \frac{Da}{m}$$

"a perfectly general relation which holds good whatever may be the nature, form or arrangement of the spectroscope train."

Since the above paper was published I have prepared tables giving the values of R, p, and P for values of r ranging from 25,000 to 1,000,000, values of $\Delta\lambda$ from 0.01 to 1.00 tenth-meters ($0^{mm}.000000001$ to $0^{mm}.0000001$) and values of $s\,\psi$ from 0.0005 to 0.020 ($s = 0^{mm}.005$ to $0^{mm}.3$, $\psi = \frac{1}{40}$ to $\frac{1}{10}$). All values are computed for $\lambda = 5500$ tenth-meters, that being the mean wave-length for the brightest part of the visible spectrum.

EXPLANATION OF THE TABLES AND REMARKS.[2]

An inspection of (1) shows that instead of diminishing continuously with increased slit width the purity of the spectrum first actually increases up to the point

$$s\,\psi \cong \tfrac{1}{5}\,\lambda.$$

For, as may be easily proved, the expression for p becomes a maximum when

$$s\,\psi = \frac{\lambda}{2\,(1 + \sqrt{2})} \cong \tfrac{1}{5}\,\lambda. \tag{4}$$

Two close lines in the spectrum are therefore *more easily resolved when the slit has the small finite width given by* (4) *than when it is infinitely narrow.* This increased resolving power is due to the same effect as is produced by stopping out the central portion of the spectroscope aperture, *i. e.*, by a strengthening of the center of the diffraction image of the slit relatively to the

[1] "General Considerations respecting the Design of Astronomical Spectroscope," *Ap. J.*, **1**, 52, January 1895.

[2] See also recent paper by the writer "On the Resolving Power of Telescopes and Spectroscopes for Lines of Finite Width," *Phil. Mag.*, **43**, 317, May 1897, and *Mem. Spettr. Ital.*, **26**, 1, Jan. 1897.

edges. When the slit is wider than indicated by (4) (as it generally must be in order to obtain sufficiently bright spectra), the purity is diminished. To find the point at which it is equal to the theoretical resolution r we put

$$s\psi + \frac{\lambda^2}{2s\psi + \lambda} = \lambda$$

which gives at once

$$s\psi = 0 \text{ or } s\psi = \tfrac{1}{2}\lambda$$

or the theoretical purity is *still equal to the theoretical resolving power when the slit width is two and one-half times that required for maximum purity.*

Since the expressions for R (2) and P (3) are similar in form to that for p (1) just considered the same conclusions will hold. In the case of R the maximum value is attained when

$$r\Delta\lambda = \frac{1.5\,\lambda}{\sqrt{7}+2} \cong \tfrac{1}{3}\lambda.$$

and the value of R is again equal to r when

$$r\Delta\lambda = \tfrac{3}{4}\lambda.$$

Hence for small values of either r or $\Delta\lambda$ the limiting resolving power will be greater than the theoretical resolving power of the instrument. But for any given value of $\Delta\lambda$ the value of R increases asymptotically with r towards a certain limit R_{max} which will evidently be

$$R_{max} = \frac{\lambda}{\frac{4}{7}\Delta\lambda} = 1.75\frac{\lambda}{\Delta\lambda}$$

or the maximum limiting resolving power of any instrument cannot be greater than one and three-quarter times the ratio between the mean wave-length and "width" of the spectral lines under examination.[1]

Our knowledge of the width of spectral lines under different conditions is at present very limited. Various hypotheses, of which the most noted are those of Lommel, Jauman, Galitzin, and Michelson, have been advanced to account for the broaden-

[1] This is on the assumption (see previous paper) that the distribution in intensity in the spectral lines follows the exponential law (Maxwell). As will be presently seen we can attain a somewhat greater practical purity P than this.

ing of the lines under varying conditions of temperature and pressure, and to give us a numerical measure of the amount, but they are all more or less unsatisfactory. Michelson's recent experimental work with the interferometer has given us our most exact knowledge of the widths of some few bright lines in the spark spectra of some of the metals under different pressures. In each case the exponential law of distribution is assumed, and the quantity given is δ, the "half width," which was defined in the preceding paper. It has been assumed as before that the effective range of wave-length $\Delta\lambda$ is about 4δ.

Table I contains a brief summary of some of the results obtained:

TABLE I.

Substance	Line λ	Character of source	Pressure in mm.	δ tenth-meters	$\Delta\lambda = 4\delta$
Hydrogen	Hα* 6565	Vacuum tube	Very low	.047	$\Delta\lambda' = 0.328$*
	" "	" "	50	.098	$\Delta\lambda' = 0.532$*
	" "	" "	100	.134	$\Delta\lambda' = 0.696$*
	" "	" "	200	.230	$\Delta\lambda' = 1.06$ *
Sodium	D_1* 5890	Vacuum tube	Very low	.005	0.020
	Not stated	Not stated	100	.09	0.36†
	" "	" "	200	.16	0.64†
	D_1* 5890	Bunsen flame	atmospheric	.05‡	0.27*
Cadmium	Red 6439	Vacuum tube, temp. about 280	Very low	.0065	0.026
	Green 5086	Vacuum tube, temp. about 280	" "	.0050	0.020
	Not stated	Not stated, probably spark	100	.05	0.200†
	" "	Not stated, probably spark	200	.08	0.32†
	" "	Not stated, probably spark	400	.14	0.56
Mercury	Green 5461	Vacuum tube, temp. about 100	Very low	.003‡	0.012

NOTES TO TABLE I.

* The red hydrogen line is a double, the distance between the components being about 0.14 tenth-meters. The value given for δ is for each component, and the total effective width of the double line is therefore $\Delta\lambda' = 4\delta + 0.14$. The same is true of

each of the D lines (according to Michelson each is made up of at least four components), the distance between the centers of the principal components being 0.07. When the density is low these components are therefore separated by much more than their own width, but when it is high (as in the Bunsen flame) each component broadens and overlaps the other so that the total effective width is as in the case of the H line $\Delta\lambda' = 4\delta + 0.07$.

† There would seem to be some discrepancy between these results, which are given in the ASTROPHYSICAL JOURNAL for November 1895, p. 251, and the results previously obtained with the vacuum tube—(*Phil. Mag.*, September 1892, p. 280).

‡ Calculated from data given in *Phil. Mag.*, September 1892, p. 280.

The values of R, R_{max}, and $\frac{r}{R}$, for different values of r and $\Delta\lambda$, are given in Table II:

The vertical columns show the increase in the value of R with an increase in $\Delta\lambda$ for a given value of r; the horizontal lines show the increase in R with r for a given width of line. The last column gives the maximum resolving power R_{max} that can be obtained when the lines have the width $\Delta\lambda$ given in the first column.

We see that in general we will very nearly reach this limit when the theoretical resolving power r is about twice R_{max}. The additional gain in R obtained by further increase in r would not be worth the expense of the larger instruments required and the sacrifice in brightness necessary. Indeed, in most cases it would hardly be advisable to use a value of r greater than one to one and one-half times R_{max}, as with this we will have already attained from $\frac{3}{4}$ to $\frac{7}{8}$ of the limiting resolving power. The finest lines so far found (see Table I) have a width $\Delta\lambda$ of not less than 0.01 tenth-meter. For this width the value of R_{max} is 950,000, and the maximum theoretical power which it would be advisable to use would therefore be about 1,400,000, corresponding in the case of a grating[1] to an aperture of from 18 to 20 inches. On the other hand, for some of the wider lines, such as those of hydrogen in the vacuum tube and of many bright metallic lines in arc-spectra, there would be no advantage whatever in using

[1] See paper "Further Notes on Astronomical Spectroscopes," *Ap. J.*, **3**, 180, March 1896; also "Resolving Power of Spectroscopes for Lines of Finite Width;" *Phil. Mag.*, May 1897.

TABLE II.

$\lambda = 5500$ tenth-meters.

$\Delta\lambda$ tenth-meters	r=25,000		r=50,000		r=100,000		r=200,000		r=500,000		r=1,000,000		R_{max}
	r/R	R	r/R	R	r/R	R	r/R	R	r/R	R	r/R	R	
0.01	0.98	25,400	0.97	51,600	0.95	105,600	0.94	212,800	1.04	480,000	1.39	722,000	962,000
0.02	0.97	25,800	0.95	52,800	0.94	106,400	1.00	200,000	1.39	361,000	2.29	437,000	481,000
0.04	0.95	26,400	0.94	53,200	1.00	100,000	1.24	161,700	2.29	219,000	4.27	234,000	240,000
0.06	0.94	26,600	0.96	52,400	1.10	90,900	1.56	128,500	3.27	153,000	6.30	159,000	160,000
0.08	0.94	26,600	1.00	50,000	1.24	80,800	1.91	104,600	4.27	117,000	8.35	120,000	120,000
0.10	0.95	26,400	1.04	48,000	1.39	71,900	2.29	87,300	5.28	95,000	10.41	96,000	96,000
0.12	0.96	26,200	1.10	45,500	1.56	64,300	2.67	75,000	6.30	79,400	12.50	80,000	80,000
0.14	0.97	25,800	1.16	42,900	1.73	57,700	3.06	65,000	7.33	68,000	14.50	69,000	69,000
0.16	1.00	25,000	1.24	40,400	1.91	52,300	3.46	58,000	8.35	60,000	16.60	60,000	60,000
0.18	1.02	24,600	1.31	38,100	2.10	47,700	3.86	52,000	9.38	53,000	18.70	53,000	53,000
0.20	1.04	24,000	1.39	36,000	2.29	43,700	4.27	46,800	10.41	48,000	20.75	48,000	48,000
0.25	1.12	22,400	1.60	31,200	2.77	36,100	5.28	37,900	13.00	38,000	25.9	38,000	38,000
0.30	1.20	20,800	1.85	27,000	3.27	30,600	6.30	31,800	15.60	32,000	31.1	32,000	32,000
0.35	1.29	19,300	2.05	24,400	3.76	26,600	7.33	27,000	18.17	27,000	36.3	27,000	27,000
0.40	1.39	18,000	2.29	21,800	4.27	23,400	8.35	24,000	20.75	24,000	41.4	24,000	24,000
0.50	1.60	15,600	2.77	18,000	5.28	18,900	10.41	19,000	25.90	19,000	51.8	19,000	19,000
0.60	1.82	13,700	3.27	15,300	6.30	15,900	12.47	16,000	31.1	16,000	62.2	16,000	16,000
0.80	2.29	10,900	4.27	11,700	8.35	12,000	16.61	12,000	41.4	12,000	82.9	12,000	12,000
1.00	2.77	9,000	5.28	9,500	10.41	9,600	20.75	9,600	51.8	9,600	103.6	9,600	9,600

a resolving power greater than 20,000 to 25,000, for which a grating of $\frac{1}{2}$ inch aperture, or 5, 60° prisms of $1\frac{1}{4}$ inches aperture would suffice. For solar spectrum work in which the lines are not likely to be narrower than $\frac{1}{20}$ tenth-meter,[1] our present 5 and 6-inch gratings will do nearly all that we could hope to attain with larger apertures,[2] unless indeed there should be some marked advantage in particular cases in the use of the first and second orders of spectra, rather than the higher orders.

The preceding conclusions are all based on the assumption that the maximum practical resolving power r_0, which has been assumed to be equal to $1.5\frac{b}{\lambda}$ and which corresponds to an angle of deviation of about 90° ($\theta = i = 45°$ to 50°), can be utilized. When for any reason this is not the case, whether because of the inaccuracies of ruling, the faintness of the higher orders of spectra, or the character of the mounting, a corresponding larger aperture must be made use of. If, for example, we consider the maximum angle of deflection to be 60° (which, from purely mechanical considerations, is about the largest possible angle that can be used in the ordinary Rowland mounting), we have for r_0

$$r = \frac{7}{8}\frac{b}{\lambda}.$$

In order to attain the same resolving powers R as before the apertures must be increased about 75 per cent. If we assume a maximum angle of 45°, which in practice is not often exceeded in our present gratings, the apertures would have to be increased by over 100 per cent., and we should therefore need to attain the full limiting resolving power R_{max}.

For lines $\Delta\lambda = .01$ tenth-meter, an aperture of at least 1^m.

For lines $\Delta\lambda = .02$ tenth-meter, an aperture of at least 50^{cm}.

[1] In the case of faint lines the apparent width may sometimes be less than this, because of the rapid falling off in intensity towards the edges of the line. For this reason estimates of pressure based upon the apparent visual widening of lines may sometimes be greatly in error.

[2] The latter would, however, be advantageous in giving increased accuracy and increased photographic resolution by reason of the greater linear dispersion. See *Ap. J.*, **1**, 233, and **2**, 264.

For lines $\Delta\lambda = .05$ tenth-meter (solar work), an aperture of at least 25^{cm}.

By an inspection of Table II it will be seen that while for narrow lines and small resolving power the ratio $\frac{r}{R}$ is very nearly unity and that formula (1) therefore represents very closely the purity of the spectrum, the same is by no means true for wide lines and large resolving powers. In the extreme case figured in the table the value of this ratio rises as high as 100. In order to show more clearly the influence of this factor on the purity of the spectrum under different conditions, Table III has been prepared, showing the values of P for different slit apertures, from $0^{mm}.005$ to $0^{mm}.3$, different widths of lines from 0.01 to 1.00 tenth-meters and resolving powers varying from $r =$ 25,000 to $r = 1,000,000$. For comparison the values of p are given for each slit width and resolving power, and also the value p' calculated from the old formula for purity.[1] An inspection of the table shows at once how greatly in error estimates of purity based upon this old formula may be in some very common cases. Take for example the case of a spectroscope having a resolving power of 200,000 (5-inch grating, 20,000 lines, second order), working with an angular slit-width such that $s\psi = .005$ ($s = \frac{1}{50}^{mm}$, $\psi = \frac{1}{40}$, as in the concave grating). The value of p (1) is about 158,000, while the value of P varies from 163,000 to 10,000. The value of p' (old formula for purity) for the same case is only 105,000. It is, therefore, in this case, from 50 to 1000 per cent. in error. In case of larger resolving powers ($r = 1,000,000$) it may be as much as sixty times too great. In general, of course, the large values of $\Delta\lambda$ that give rise to the smaller values of P will not be used for visual work as there is, as already indicated, but little gain in practical resolving power or purity when the value of r is greater than the value of R_{max} given in Table II. But in photographic work it is, as already has been shown in a previous paper, a great advantage to use (for extended sources) a short camera and a very high resolving

[1] See article "Spectroscopy," *Enc. Brit.*, **22**.

TABLE III.

$\lambda = 5500$ tenth-meters.

s	ψ radians	$s\psi$		$\frac{w}{4\delta}$	$\frac{r}{25000}$	$\frac{r}{50000}$	$\frac{r}{100000}$	$\frac{r}{200000}$	$\frac{r}{500000}$	$\frac{r}{1000000}$
				.01	20000	40200	81200	163200	389000	662000
.005	$\frac{1}{10}$			.05	20300	40600	77800	132400	194000	207000
			P	.10	20300	38900	66200	91400	103400	102200
.010	$\frac{1}{20}$	0.0005		.50	15100	19400	20700	20400	19900	19900
				1.00	9700	10300	10200	10000	9800	9700
.020	$\frac{1}{40}$		p		19800	39600	79100	158200	396000	791000
			p'		13100	26200	52400	104800	262000	524000
				.01	12400	24800	49700	99400	243000	454000
				.05	12400	24800	48700	90900	166000	202000
.010	$\frac{1}{10}$		P	.10	12400	24400	45500	74300	101500	108000
		0.001		.50	10900	16600	20200	21500	20400	19900
.015	$\frac{1}{15}$			1.00	8300	10100	10800	10300	10000	9800
			p		12300	24600	49100	98200	245000	491000
			p'		8900	17800	35500	71000	177000	355000
				.01	6700	13400	26700	53500	133000	259000
				.05	6700	13400	26600	51900	113600	171000
.020	$\frac{1}{10}$		P	.10	6700	13300	25900	47800	85700	103000
		0.002		.50	6400	11400	17100	20600	21000	20600
.030	$\frac{1}{15}$			1.00	5700	8500	10300	10600	10300	10000
			p		6650	13350	26700	53400	133500	267000
			p'		5400	10800	21600	43200	108000	216000
				.01	4500	9100	18100	36200	90200	178000
				.05	4500	9100	18000	35600	83100	141000
.030	$\frac{1}{10}$		P	.10	4500	9000	17800	34200	75700	95300
		0.003		.50	4400	8300	14100	19100	21100	20800
.045	$\frac{1}{15}$			1.00	4200	7600	9500	10500	10400	10100
			p		4500	9100	18100	36200	90500	181000
			p'		3900	7800	15500	31000	77500	155000
				.01	2700	5400	10900	21800	54500	108000
				.05	2700	5400	10900	21800	52900	97300
.050	$\frac{1}{10}$		P	.10	2700	5400	10800	21400	48800	77100
		0.005		.50	2700	5300	9700	15400	20600	21100
.075	$\frac{1}{15}$			1.00	2600	4900	7700	9900	10500	10300
			p		2700	5400	10900	21800	54500	109000
			p'		2500	5000	9900	19800	49500	99000
				.01	1400	2800	5500	11000	27500	54900
				.05	1400	2800	5500	11000	27200	53000
.10	$\frac{1}{10}$		P	.10	1400	2800	5500	10900	26500	48800
		0.010		.50	1400	2700	5300	9800	17300	20600
.15	$\frac{1}{15}$			1.00	1400	2600	4900	7800	10300	10500
			p		1400	2800	5500	11000	27500	55000
			p'		1300	2600	5200	10400	26000	52000
				.01	700	1400	2800	5600	14000	27500
				.05	700	1400	2800	5500	13700	27200
.20	$\frac{1}{10}$		P	.10	700	1400	2800	5500	13600	26500
		0.020		.50	700	1400	2700	5300	11600	17300
.30	$\frac{1}{15}$			1.00	700	1400	2600	4900	8600	10300
			p		700	1400	2800	5600	14000	28000
			p'		650	1300	2600	5200	13000	26000

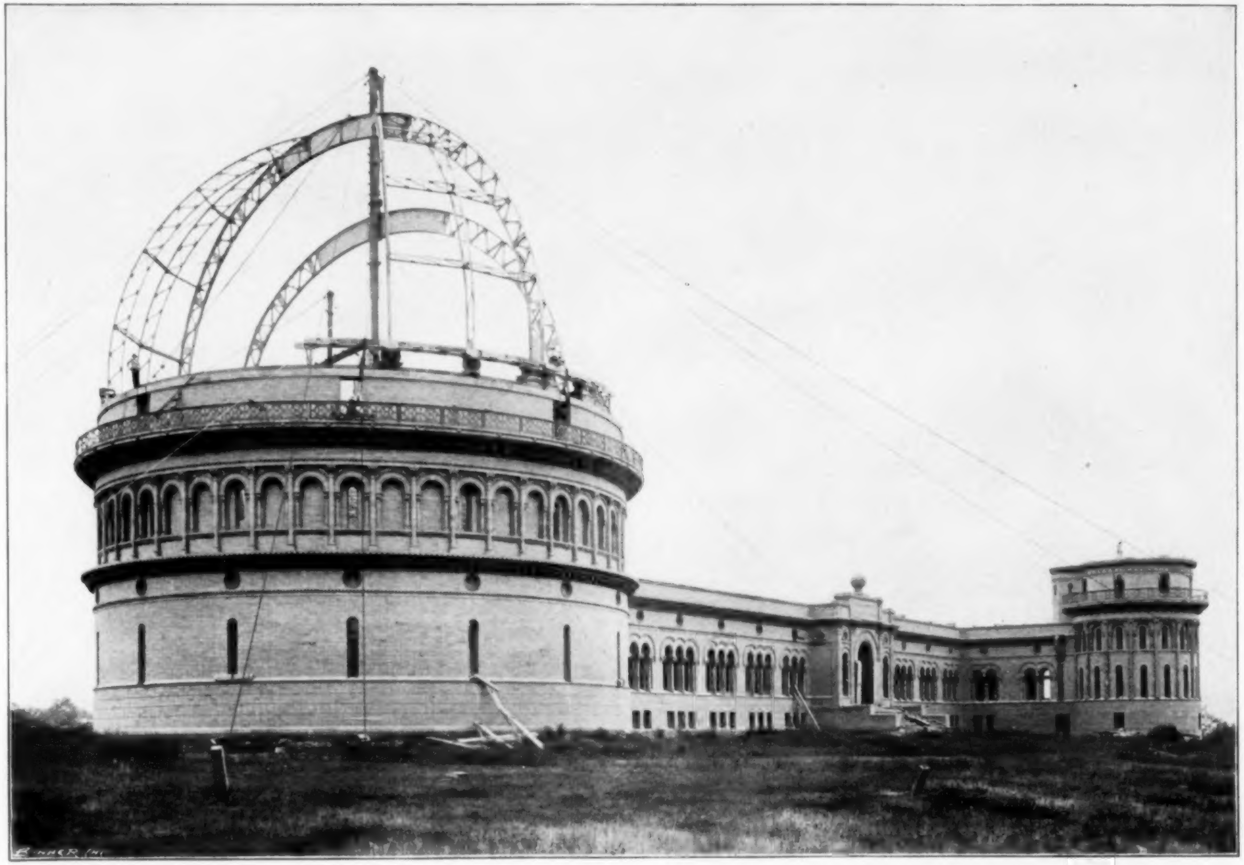
power, in order to attain a given degree of photographic purity. Another point which is of considerable practical importance in this connection is that for these large values of $\frac{r}{R}$ the purity of the spectrum may be maintained constant or even actually improved over a wide range of those slit widths actually used in practice. For the maximum value of P (as of p) will be attained when

$$s \cong \tfrac{1}{5} \frac{r}{R} \lambda.$$

For $r = 200{,}000$, $\Delta\lambda = 1.00$, $\frac{r}{R} = 20.75$, and the maximum value of P is therefore attained when the value of $s\psi$ is about 4.15λ, or about .0023, corresponding for the usual spectroscope to a slit width of about $\frac{1}{30}^{mm}$. Under the same circumstances the practical purity is still as great when the slit width is $\frac{1}{15}^{mm}$ as when it is zero. For still higher resolving powers the maximum allowable widths of slit are still greater. Even with such low values of $\frac{r}{R}$ as 2 or 3 (corresponding to lines as fine as those sometimes found in the solar chromosphere, *i. e.*, 0.2 to 0.25 tenth-meter), and resolving powers of only 100,000, the purity remains undiminished up to values of $s\psi = \lambda$ to 1.5λ, (.0005 to .0008), or to slit widths (with the concave grating) of from $\frac{1}{80}$ to $\frac{1}{30}^{mm}$.

YERKES OBSERVATORY,
February 1897.

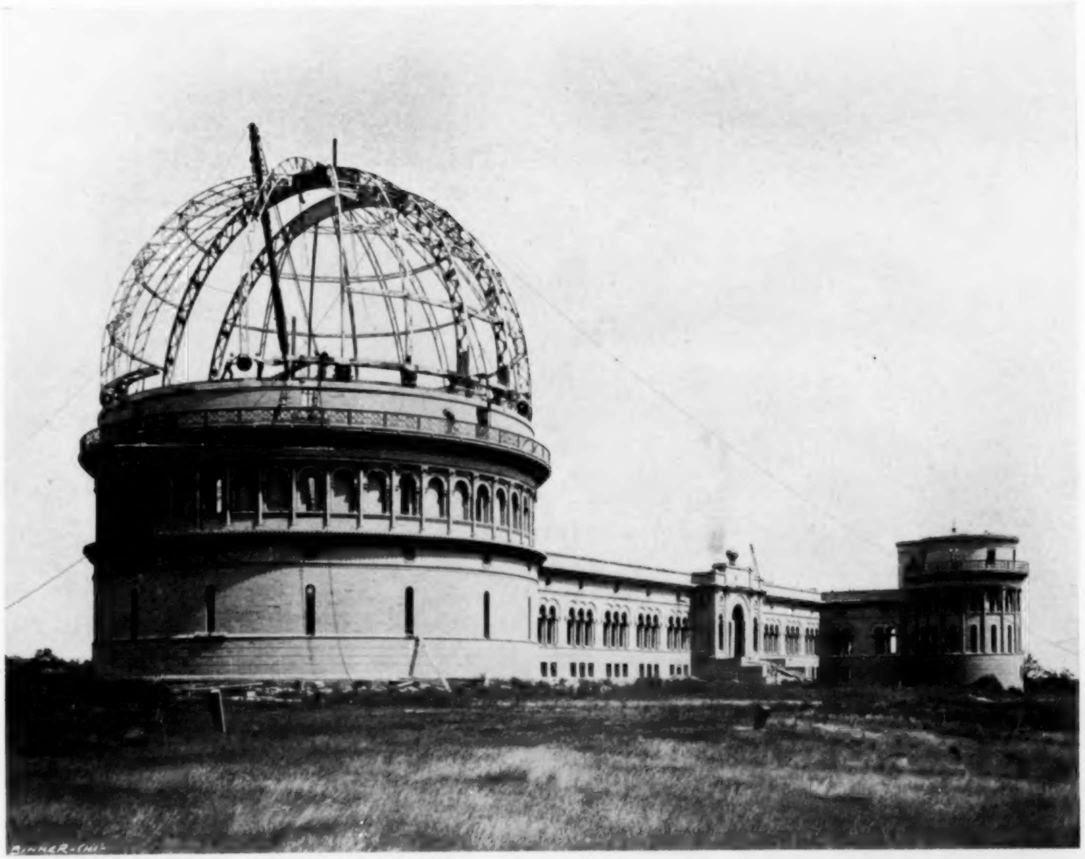
PLATE II.



THE NINETY-FOOT DOME OF THE YERKES OBSERVATORY, AUGUST 22, 1896.

ERECTING THE CENTRAL GIRDERS.

PLATE III.



THE NINETY-FOOT DOME OF THE YERKES OBSERVATORY, AUGUST 27, 1896.

ERECTING ONE OF THE SMALLER GIRDERS.

THE YERKES OBSERVATORY OF THE UNIVERSITY OF CHICAGO.

IV. THE FORTY-INCH TELESCOPE, DOME AND RISING-FLOOR.[1]

By GEORGE E. HALE.

THE great tower which contains the forty-inch telescope of the Yerkes Observatory is at the western extremity of the main building. It is entered from the long corridor by means of a broad marble stairway, the upper landing of which is level with the rising-floor when the latter is at its lowest position. Two balconies encircle the inner wall of the tower. The upper one leads through doors at the cardinal points, to an outer balcony from which any part of the sky can be seen. The rising-floor is at this level when raised to its highest position. Twenty-three feet below, at the other limit of the floor's motion, is the second inner balcony. An iron stairway, following the curve of the wall, connects the balconies with each other and with the ground floor of the tower.

For the important purpose of ventilating the observing room the tower wall is pierced with thirty-two windows, arranged in three rows. These are intended to be kept open the greater part of the time, except when observations are being made. As a further means of maintaining the temperature of the interior closely on a par with that of the outer air, the doors leading from the body of the building are made double, and additional precautions are taken against the admission of hot or cold air.

The wall terminates at a height of fifty-two feet from the ground in a heavy stone coping, to which is anchored the circular track of T rails upon which the dome revolves.

[1] For previous articles in this series see the March, April, and May numbers of the ASTROPHYSICAL JOURNAL.

THE DOME.[1]

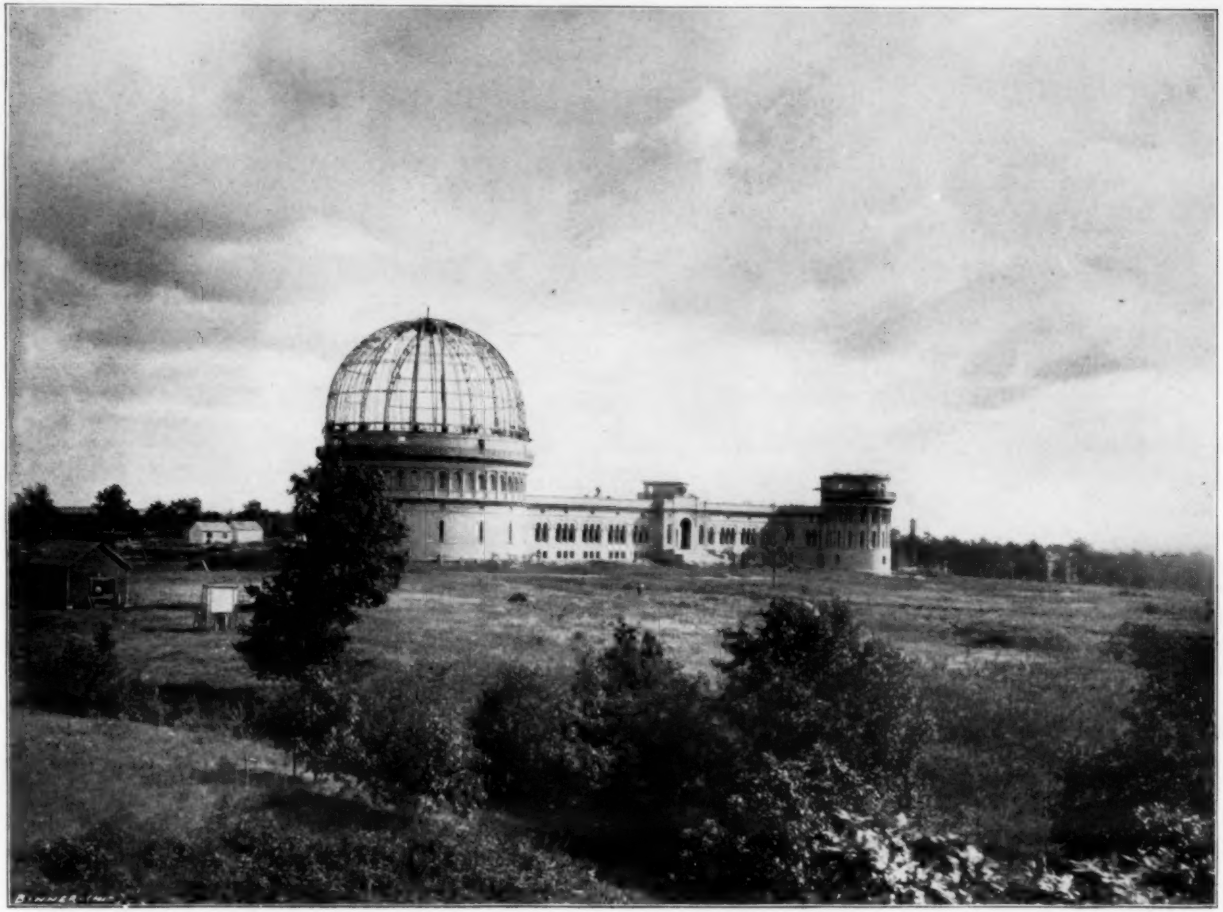
The great dome, like the rising-floor and the mounting of the forty-inch telescope, was designed and constructed by Messrs. Warner & Swasey, of Cleveland, Ohio, the well-known builders of the mounting of the Lick telescope. It is ninety feet in diameter, sixty feet high and weighs 140 tons. The construction of the steel framework will be easily understood from an inspection of the accompanying plates, which are reproductions of photographs taken while the dome was in process of erection. Two very heavy girders (Plate II) stand on either side of the observing slit and form the nucleus of the structure. They are carried by eight wheels, two at either end of each girder. The remainder of the framework is built up of smaller girders, bolted to the great central pair, and tied together with horizontal members. Plate III, from a photograph taken just as one of the small girders was being hoisted into place, shows how each of these members, with a wheel bolted to its lower extremity, was built into the ring which forms the base of the dome. After the various parts of the steel framework had been put in place, they were fastened together with hot rivets. A sheathing of wood (Plate V) was then fitted to the framework, and this in turn was covered with roofing tin. This wood covering is very advantageous in completely doing away with a difficulty commonly experienced under certain atmospheric conditions with all-metal domes, viz., the condensation of water, which drops upon the instrument and floor.

The thirty-six wheels upon which the dome revolves are each 36 inches in diameter. The journals, provided with roller bearings, are so mounted that the wheels are left free to adapt themselves to any possible inequalities of the track. The dome is revolved by means of an endless cable driven by an electric motor connected with the turning mechanism. Provision is also made for moving the dome by hand from the rising-floor or balconies.

The observing slit, thirteen feet wide, extends from the hori-

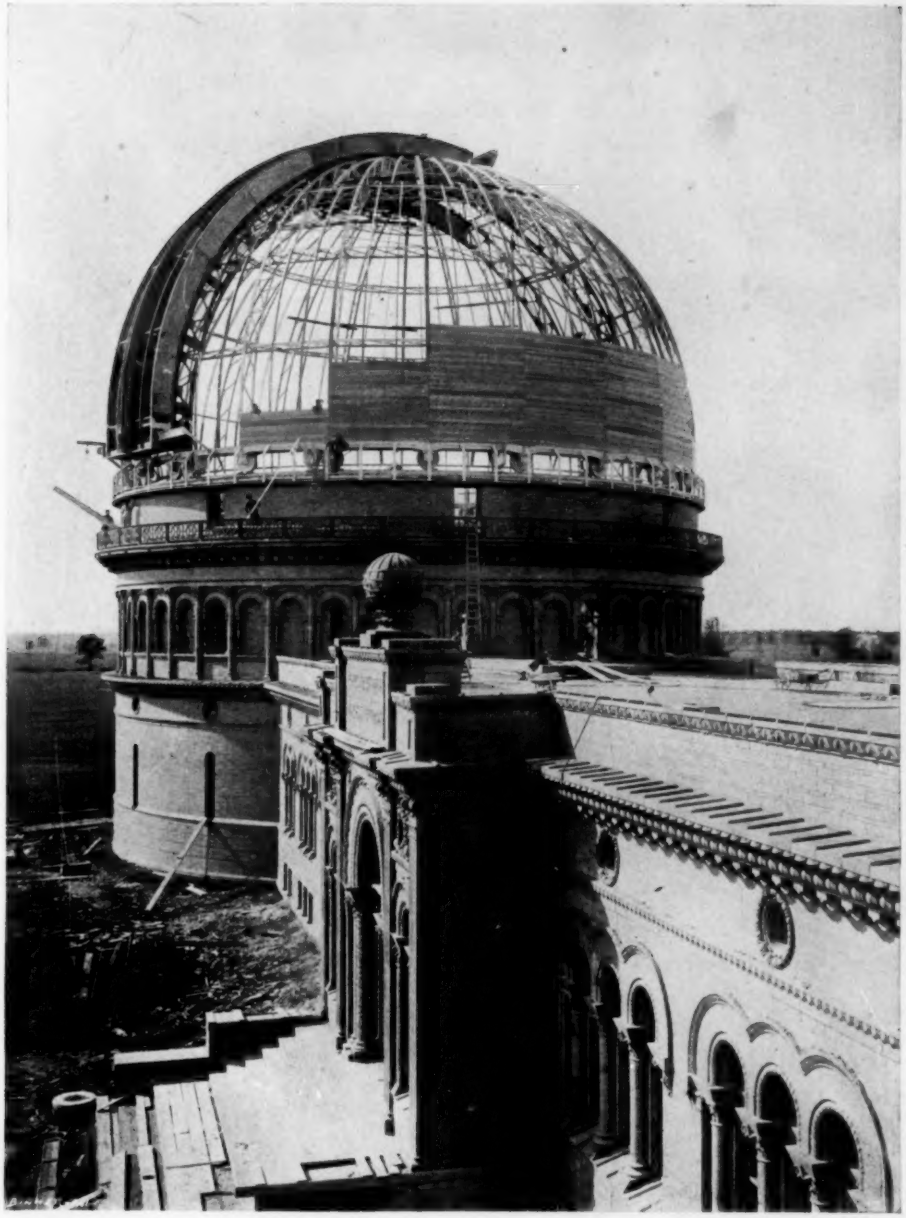
[1] For many of the details embodied in the following description of the dome, rising floor, and telescope mounting I am indebted to Messrs. Warner & Swasey.

PLATE IV.



THE NINETY-FOOT DOME OF THE YERKES OBSERVATORY, SEPTEMBER 9, 1896.

PLATE V.



SHEATHING THE NINETY-FOOT DOME OF THE YERKES OBSERVATORY, OCTOBER 2, 1896.

zon to a point five feet beyond the zenith. The two shutters which cover this opening are eighty-five feet long. Roller-bearing wheels attached to the upper and lower ends of each shutter move on tangential tracks attached to the dome. The mechanism for operating them is so arranged that the two shutters move simultaneously from the center outward, remaining parallel to each other in all positions.

Within these shutters two canvas curtains, stretched across the opening, are mounted on tracks extending from below the horizon to a point about 50° beyond the zenith. These may be adjusted so as to shelter the telescope from the wind, in whatever direction it may be pointing. By this simple means, which is also used at the Nice and Meudon Observatories, it is expected that one of the greatest difficulties experienced in observational work with great telescopes will be in large degree overcome.

THE RISING-FLOOR.

The problem of providing suitable means of rendering accessible the eye-end of an equatorially mounted telescope, for all positions of the instrument, was happily solved by the invention of the rising-floor. When the Lick telescope was in process of construction, and the difficulty of observing objects at widely different altitudes with a telescope of such great focal length had been carefully considered, it was suggested by Sir Howard Grubb that the entire floor of the observing room be arranged to rise and fall. In this way the telescope would be equally available for observation at all altitudes. The plan was adopted at the Lick Observatory, and has since been used at the new United States Naval Observatory and at one or two smaller observatories abroad.

At the Yerkes Observatory the need for such a rising-floor was greater than at any other existing institution. Not only is the focal length (62 feet) of the large telescope greater than that of other equatorial refractors, but it was felt that provision should be made for attaching proportionally large spectroscopes. At the Lick Observatory the floor has a range of motion of 16

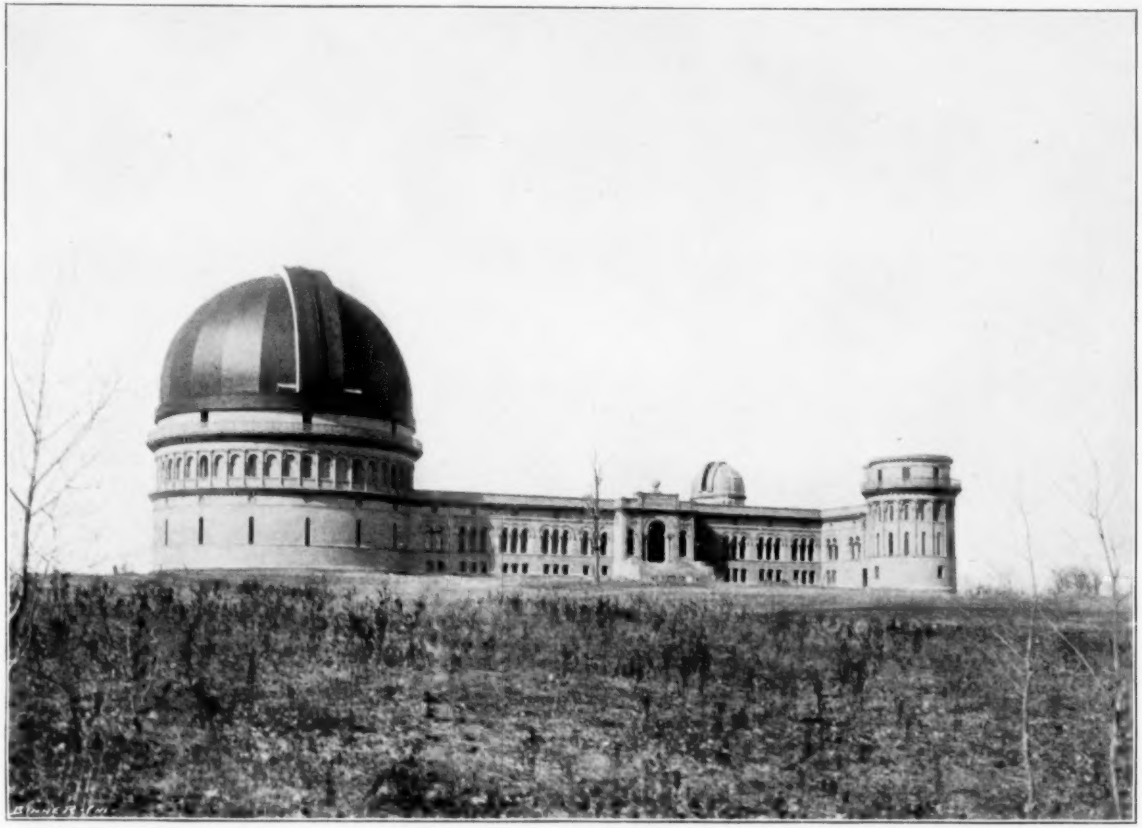
feet, and is moved by hydraulic rams. To provide sufficient room for a solar spectroscope (9 feet long) for use with the forty-inch telescope, it was found that the rising floor of the Yerkes Observatory must be 75 feet in diameter, and have a vertical motion of 23 feet. Hydraulic rams could not be used, on account of the danger of freezing in the severe cold of Wisconsin winters.

The rising-floor designed by Messrs. Warner & Swasey seems to meet these conditions in a satisfactory manner. The steel construction is much lighter, though not less rigid, than that of the Lick floor, and the total weight is 37½ tons. Instead of the hydraulic rams used elsewhere, four pairs of wire cables 90° apart, support the floor. These pass over large sheaves and are attached at their opposite ends to counter-balance weights moving on guides in four steel columns. At the base of each column is a drum four feet in diameter, around which is wound a wire cable fastened to the lower side of the floor. The other end of this cable is attached to the bottom of the counterweights. Each drum has on its circumference a large worm gear, and the worm which drives it is carried on a shaft geared to the three other shafts that drive the corresponding drums. The four shafts are operated from a single point by means of an electric motor, which is controlled from a switch box on the rising-floor. By simply moving a switch the astronomer can thus bring the floor to any desired level. When the telescope is pointed to the zenith the objective is about 73 feet above the lowest position of the floor.

THE FORTY-INCH YERKES TELESCOPE.

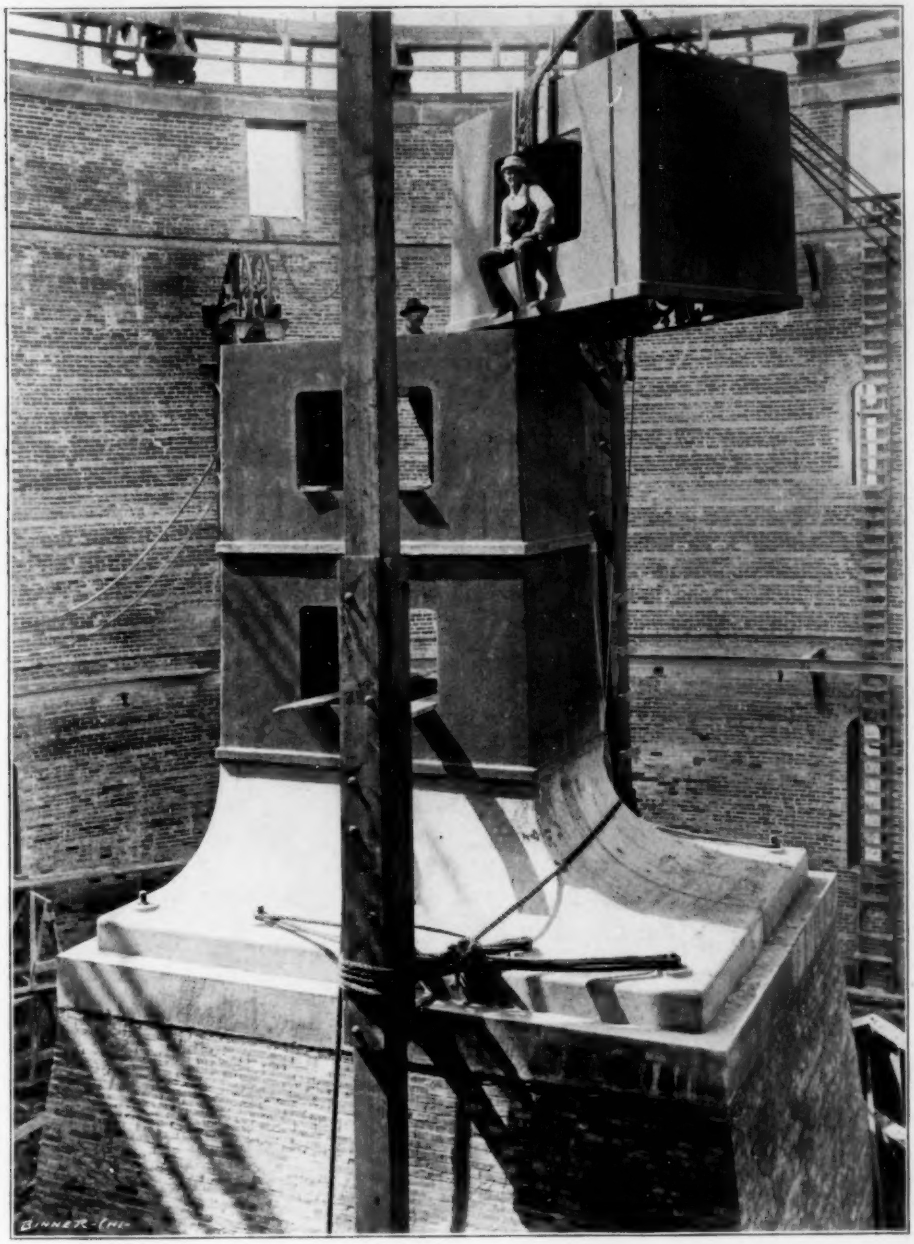
Representing as it does an increase in aperture of but four inches over the largest equatorial refractor hitherto constructed, the Yerkes telescope might not at first sight be supposed to offer any special difficulties of construction or design. As a matter of fact, however, the problem of designing a suitable mounting for the forty-inch objective was by no means a simple one. The great weight of the objective (about 1000 pounds in

PLATE VI.



SOUTH FRONT OF THE YERKES OBSERVATORY.

PLATE VII.



ERECTING THE IRON COLUMN OF THE YERKES TELESCOPE,
SEPTEMBER 8, 1896.

its cell) and the desirability of attaching an equally heavy spectroscope at the eye end made necessary the construction of a tube of exceptional rigidity. The consequent great weight of the moving parts must inevitably increase the difficulty of moving the telescope, and for this and other reasons it was decided to provide a complete system of electric motors and clamps, for the purpose of effecting the various operations usually performed by hand. It will thus be seen that the greatest experience and skill would be required of the designer of a really successful mounting.

After carefully examining most of the great telescopes in American and European observatories, the writer decided to recommend to Mr. Yerkes that the contract for the mounting be awarded to Messrs. Warner & Swasey, not only because of the well-known excellence of their workmanship, but more especially on account of the invaluable experience gained by this firm in designing and constructing the mounting of the thirty-six inch Lick refractor.

The frontispiece shows the Yerkes telescope as it appeared on May 11, 1897, when Messrs. Warner & Swasey's work had been practically completed. The cast-iron column (Plate VII) consists of four sections, tapering from 11 feet × 5 feet at the base to 10 feet × 5 feet at the junction with the head. These four sections are bolted together, and rest on a cast-iron foot 18 feet × 14 feet which is firmly anchored to a massive brick pier supported on a concrete foundation 32 feet × 28 feet × 5 feet. At the top of the column is the equatorial head, which is cast in a single piece. The column and head rise to a height of 43 feet above the lowest position of the rising-floor, and weigh 50 tons. Surrounding the head is an iron balcony, accessible from the rising-floor by means of a spiral stairway on the south side of the column, which also leads to the clock room in the upper section of the head.

The polar and declination axes are of hard forged steel, and weigh 3½ and 1½ tons respectively. The polar axis (Plate VIII), 13½ feet long, has a diameter of 15 inches at the upper

bearing and 12 inches at the lower bearing. At both of these points the friction is relieved by means of live rings of steel rolls, running in steel yokes, and held against the axis by spring levers. The lower end of the axis rests on a double set of forty hardened steel balls, one inch in diameter. The upper end carries the main driving gear, which has 330 teeth, is 8 feet in diameter, and weighs one ton. This is driven by a worm geared to the driving clock, and when clamped to the axis sets in motion a mass weighing 20 tons.

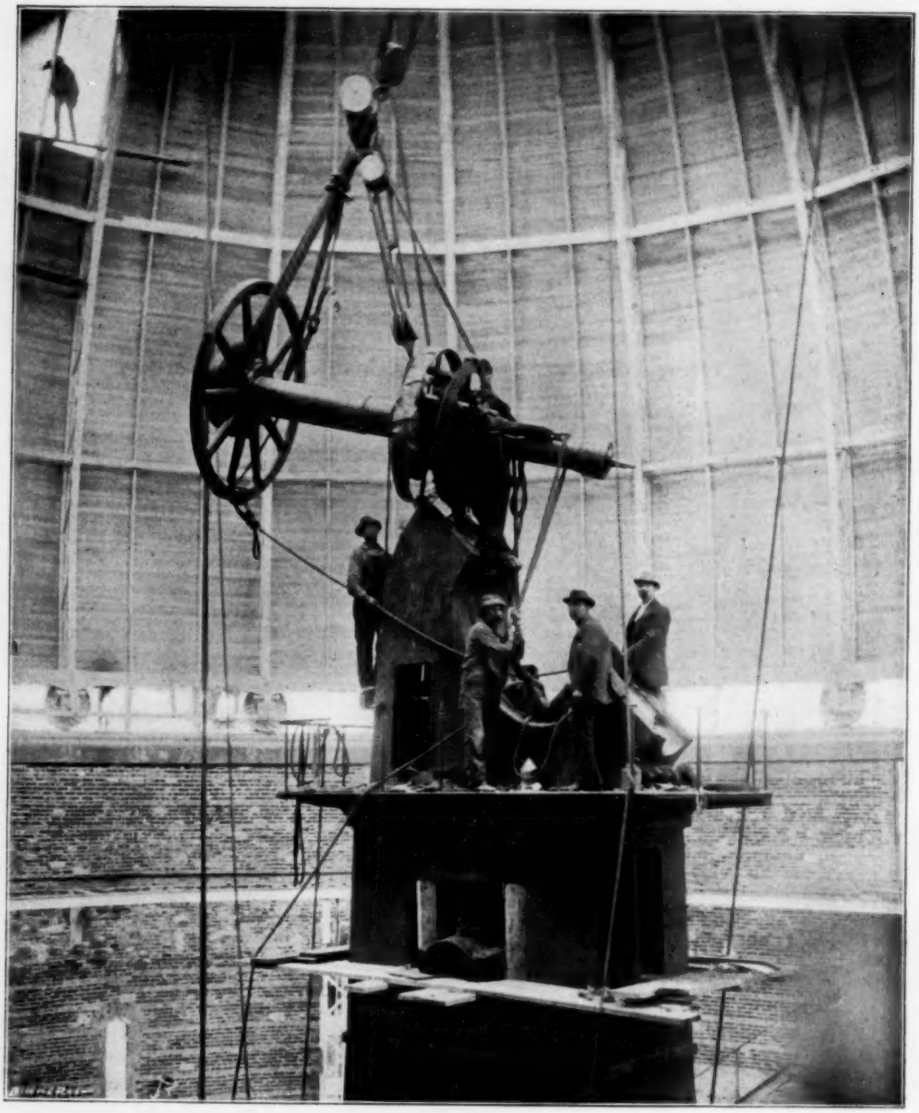
The declination axis (Plate IX) which runs in Babbitt bearings in the declination sleeve, is 12 inches in diameter and 11½ feet long. The pressure of this axis upon its bearings, amounting, with the weight of the tube, to about 8 tons, is relieved by a live ring of steel rolls, which greatly reduces the friction.

The tube is made of sheet steel, varying in thickness from $\frac{7}{32}$ inch at the center to $\frac{1}{8}$ inch at the ends. Its diameter is 52 inches at the center, 42 inches at the objective end and 38 inches at the eye end. It is 60 feet long, and weighs 6 tons. For the central section, to which the declination axis is bolted, it was considered necessary to use some material more reliable than cast-iron, which is ordinarily employed in smaller mountings. The heavy sheet steel selected for this purpose seems to be in all respects satisfactory.

The driving clock stands in the clock room (Plate X) in the upper section of the column, where it is easily reached from the spiral stairway. It is of the type used by Messrs. Warner & Swasey in all of their mountings, with additional change gears for mean solar and lunar rates. The double conical pendulum, mounted isochronously on the well-known plan long ago suggested by Professor Young, makes sixty revolutions per minute. It is provided with a simple electric control, similar in principle to the control applied by Professor Keeler to the driving clock of the Lick telescope. An electric motor automatically winds the clock when the driving weight has reached a point near the limit of its run.

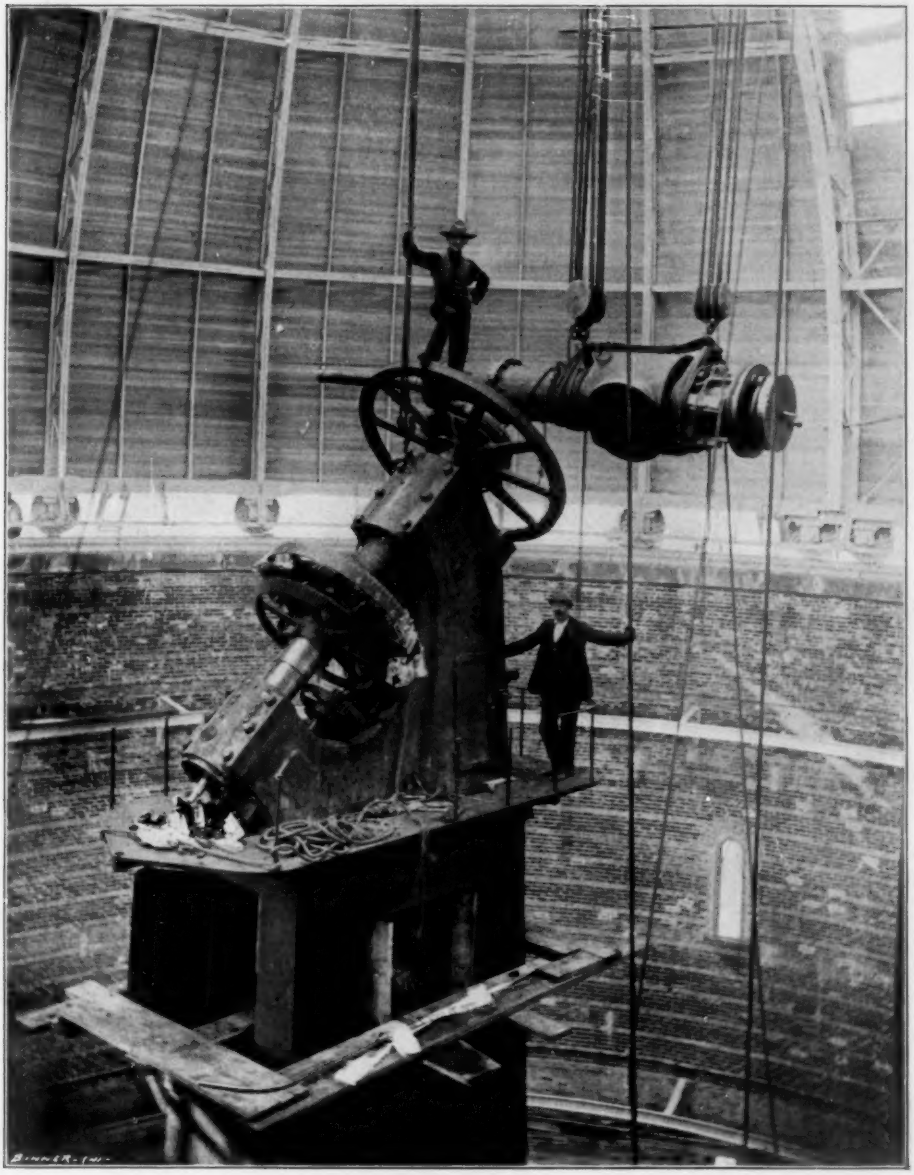
The telescope is so designed that it is in perfect balance

PLATE VIII.



ERECTING THE POLAR AXIS OF THE YERKES TELESCOPE, OCTOBER 8, 1896.

PLATE IX.



ERECTING THE DECLINATION AXIS OF THE YERKES TELESCOPE, OCTOBER 9, 1896.

with a spectroscope weighing about half a ton attached to the eye end. When the spectroscope is removed iron weights are clamped to the tube near the eye end in order to restore the balance.

The clamps and slow motions can be operated by the observer at the eye end, where the fine declination circle can also be read. An assistant on the balcony can move the telescope in both right ascension and declination, and read the fine hour circle. The divisions of the coarse circles are visible from the floor.

In addition to the ordinary appliances just referred to for actuating the quick and slow motions and clamping the telescope, a complete system of electric motions, clamps and illumination is also provided. It is rather surprising that so convenient a means of operating a large telescope, first suggested by Sir Howard Grubb, and strongly commended by Dr. Gill, has not hitherto been adopted. Conveniently placed switches at the eye end and on the equatorial head, enable the observer or his assistant on the balcony to start or stop the slow motion motors, and to clamp or unclamp in right ascension and declination, by simply pressing knobs. The quick motion motors (shown in Plate XI) are controlled from the balcony and eye end by switches. The circles are illuminated by incandescent lamps, connected with switches at the eye end and on the head. Provision is also made for electric illumination of the micrometer wires.

The forty-inch objective of the Yerkes telescope was made by the firm of Alvan Clark & Sons from disks furnished by Mantois of Paris.[1] The crown lens is about 2½ inches thick at the center and ¾ of an inch at the edge; it weighs 200 pounds. The flint lens, which is separated from the crown by a distance of 8⅜ inches, is about 1½ inches thick at the center, 2 inches thick at the edge, and weighs over 300 pounds. The lenses are mounted upon aluminium bearings in a cast-iron cell. The focal length of the objective is very nearly 62 feet.

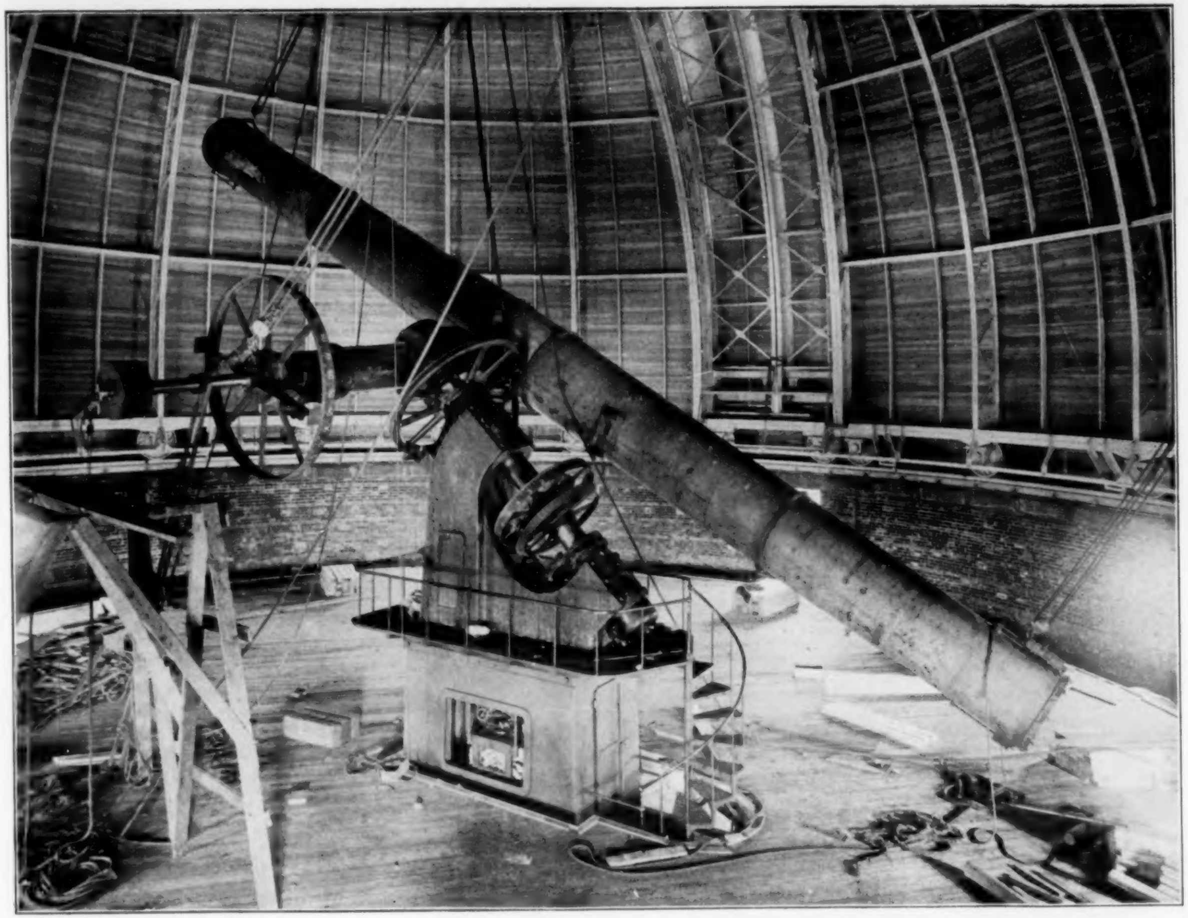
[1] An account of the manufacture of these disks, illustrated with reproductions of photographs of the rough glass blocks, is given by Mr. J. A. Brashear in *Popular Astronomy*, 1, February 1894.

The terms of the contract between Mr. Yerkes and Messrs. Alvan Clark & Sons required that the objective be examined by an "expert agent" before acceptance. At the request of the writer, Professor James E. Keeler kindly made the necessary tests at Cambridgeport in October 1895. Profesor Keeler's report has already been published in the ASTROPHYSICAL JOURNAL (**4**, 154, February 1896). After certain changes had been made in the position of the lenses in the cell, he found that "the expanded star disk was round inside and outside of the focus, uniformly illuminated, and free from wings or other appendages. Good images at the focus were obtained of stars at widely different altitudes near the meridian, the definition being in my opinion, with due allowance for atmospheric disturbance, equal to that of the Lick telescope, while the brightness of the image was of course considerably greater than with the latter instrument." . . . . "The absence of ghosts and the small amount of diffuse light when this brilliant star (Sirius) was in the field were particularly noted. The color correction of the forty-inch objective is, according to my best recollection, almost precisely the same as that of the Lick objective." The writer was led to similar conclusions from independent tests made on the same occasion.

ACCESSORIES OF THE FORTY-INCH TELESCOPE.

Micrometer.—The filar micrometer shown in Plate XI was designed and constructed by Messrs. Warner & Swasey, after suggestions by Professor Burnham. In its general form and details it is similar to the micrometer of the 36-inch at Mt. Hamilton, which has proved so satisfactory in the measurement of all kinds of difficult objects. The eyepieces were made by Steinheil & Sons, of Munich; they are of the latest and best form for micrometrical work, and give powers ranging from 150 to about 3000. The micrometer is furnished with Burnham's illuminating device giving bright wires on a dark field. Provision is also made for illuminating the wires electrically. The amount of light on the wires can be instantly changed by the

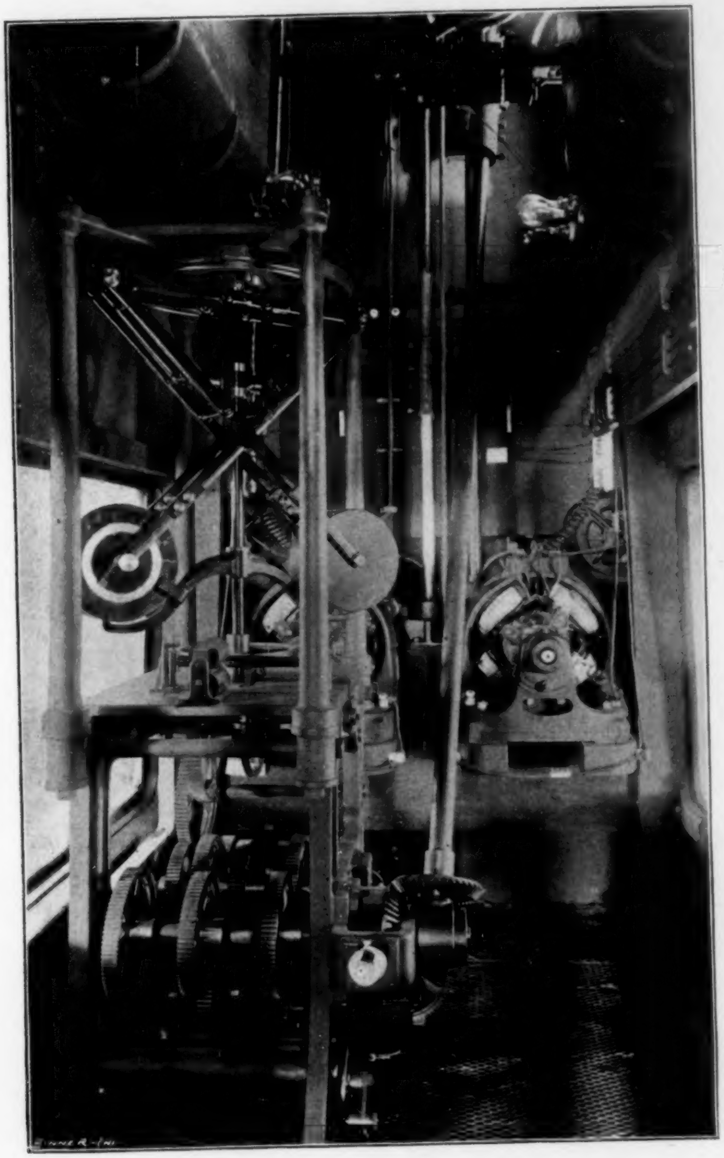
PLATE X.



MOUNTING OF THE FORTY-INCH YERKES TELESCOPE, NOVEMBER 1896.

THE RISING-FLOOR IS SHOWN AT ITS HIGHEST LEVEL.

PLATE XI.



CLOCK ROOM OF THE YERKES TELESCOPE.

observer so as to adapt the illumination to the measurement of the faintest objects which the telescope will show.

Solar spectroscope and spectroheliograph.—The combined solar spectroscope and spectroheliograph at present used with the Yerkes telescope is the instrument designed by the writer in 1889, and used in his work at the Harvard and Kenwood Observatories.[1] It has recently been remodeled in the instrument shop of the Yerkes Observatory, the lever system and moving slits formerly used being replaced by a moving collimator slit and plate of the type designed by Professor Wadsworth.[2] On account of the comparatively small angular aperture of the collimator and camera objectives, this spectroheliograph is not well adapted for use with the forty-inch telescope. The solar image at the focus of the telescope is nearly seven inches in diameter, and of this a zone only two inches wide and three inches long can be photographed in a single operation. It will therefore be necessary to obtain a larger spectroheliograph as soon as possible.

As a solar spectroscope and spectrograph the old instrument has long since demonstrated its excellence. With collimator and telescope objectives of three and one-quarter inches aperture and forty-two and one-half inches focus, and a four-inch Rowland grating having 14,438 lines to the inch,[3] the spectroscope may fairly be accounted a powerful one. Various investigations have been planned, however, which require a much higher photographic resolving power, and a larger spectroscope will be required to meet these needs.

Stellar spectrograph.—The great light-gathering power of the forty-inch telescope particularly adapts it for investigating stellar spectra. For this purpose an excellent stellar spectrograph, designed and constructed by Brashear, has been presented to the Observatory by Mr. Yerkes. This instrument is in almost

[1] An illustrated description of this instrument is given in *Astronomy and Astrophysics* **11**, 407, 1893.

[2] This JOURNAL **1**, 244, March 1895.

[3] A five-inch grating with 20,000 lines to the inch is also available for use with this spectroscope.

every respect similar to the spectrograph built by Brashear after Professor Keeler's indications for the Allegheny Observatory.[1] The collimator and camera objectives are of 1¼ inches aperture and nineteen inches focal length. A train of three flint prisms is ordinarily employed for photographic work, but in addition to these, single light and heavy flint prisms, and a Rowland grating, with long and short observing telescopes and a filar micrometer, are provided for visual observations. The collimator has a range of motion of five inches, on account of the special color curve of the forty-inch telescope. A correcting lens for photographic work in the upper spectrum will be furnished by Brashear. The slit is made with polished jaws of speculum metal, on the plan devised by Dr. Huggins. By observing with a small telescope the image reflected from the slit jaws, the task of finding a faint star or of holding the slit during an exposure upon some chosen region of a planet or other extended object, is greatly simplified. The spectrograph is provided with all necessary apparatus for producing comparison spectra. It is in every respect a very complete and satisfactory instrument.

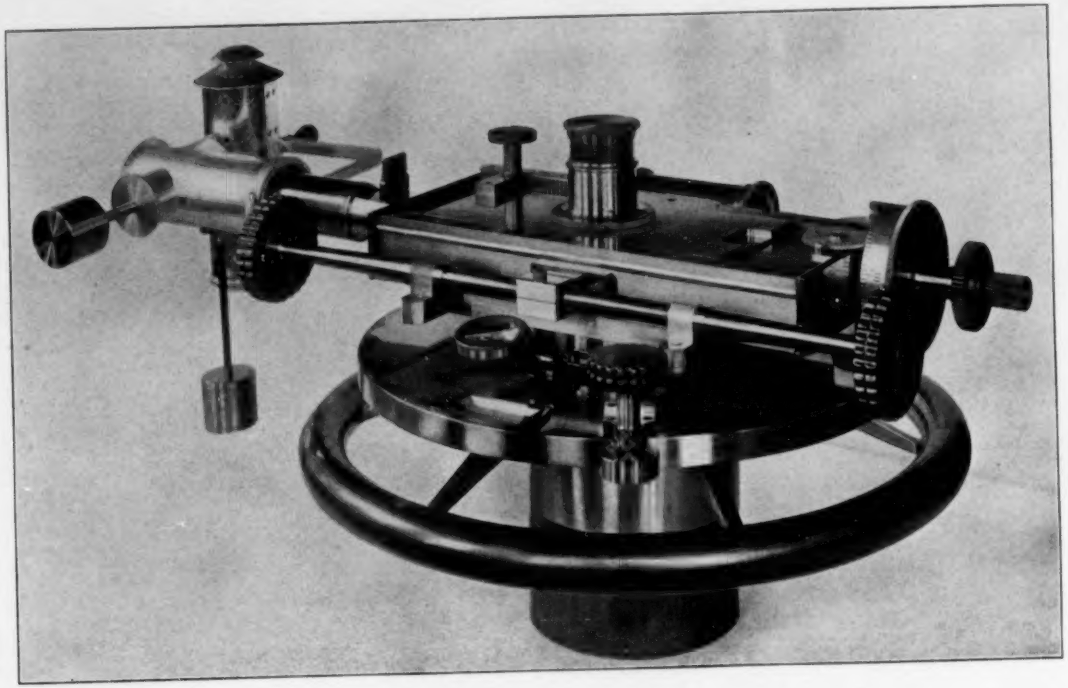
Arrangements have been made for attaching various other instruments to the eye end of the forty-inch telescope, including bolometric apparatus for experiments on the solar corona, and the twelve-inch photographic objective of the small equatorial, for use in connection with the solar work.

In the present series of articles the writer has endeavored to give some account of the material equipment of the Yerkes Observatory.[2] The forty-inch objective has recently been put in place, and the adjustments of the large telescope are being made Of the detailed plans for the investigations to be undertaken by Professors Burnham, Barnard, Wadsworth, and the writer with this and other instruments, it is unnecessary now to speak. It

[1] See *Astronomy and Astrophysics* **12**, 40, 1893.

[2] For a full statement regarding the admission of advanced students to the Yerkes Observatory see the *Annual Register* of The University of Chicago.

PLATE XII.



FILAR MICROMETER OF THE YERKES TELESCOPE.

may be said, however, that if the ideas of the present members of the staff are maintained, the work is not likely to partake of that element of sensationalism which threatens to disfigure modern observational astronomy.[1]

YERKES OBSERVATORY,
May 1897.

[1] The excellent photographs used in illustrating these articles have been made, with one or two exceptions, by Mr. Ferdinand Ellerman, Assistant in the Yerkes Observatory.

RADIATION IN A MAGNETIC FIELD.

By ALBERT A. MICHELSON.

IN the interesting and important paper of Zeeman on the influence of magnetism on the nature of the light emitted by a substance[1] there is a reference to the work of the late M. Fievez, who found that instead of a broadening of the spectral lines, there were reversals and double reversals which Zeeman has not observed.

In some cases the magnitudes to be observed are of the order of a fortieth of the distance between the sodium lines, and should be clearly seen in a good spectroscope under proper conditions; but others occur in which they are but a third or a fourth as large, and in these cases all detail is lost in diffraction effects and optical imperfections.

For the investigation of just such cases the *interferometer* is particularly adapted, and it was determined to investigate the problem with the aid of this instrument.

The first substance tried was sodium. A bead of sodic carbonate was placed in the flame of a small hand blowpipe, which could be kept under better control than a Bunsen burner. This was placed between the flat pole-pieces of a moderately large electro-magnet in the manner described by Zeeman, and the light after passing through a collimating lens entered the interferometer. The difference of path commencing at zero was increased by single turns of the millimeter screw, noting at each turn, the clearness or visibility of the interference fringes,[2] first without and then with the magnetizing current.

The curves *A* and *D*, Fig. 1,[3] show the results of this experiment. They are the envelopes of the visibility curves, the alternations of which are too rapid to show on this scale. The

[1] *Phil. Mag.*, March 1897; this JOURNAL, May 1897.

[2] *Phil. Mag.*, September 1892.

[3] Negative ordinates indicate reversal of the fringes.

abscissae are differences in path of the interfering pencils in millimeters. From these the distribution of light in the source

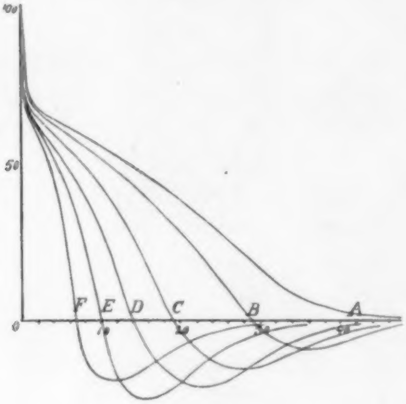


FIG. 1.

is found as described in a previous article.[1] The results are shown at *A* and *D*, Fig. 2, the first representing the appearance

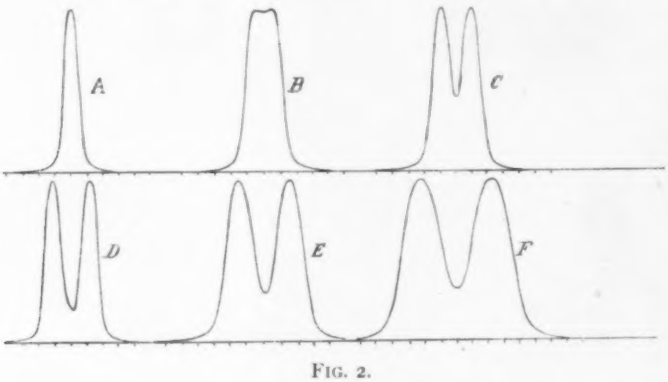


FIG. 2.

of one of the sodium lines without, and the second with the magnetizing current.

It is evident from the figures that the broadening of the line is relatively insignificant, but that it is separated into two com-

[1] *Phil. Mag.*, September 1892.

ponents of equal intensity.[1] The question at once arises whether or not this fact lends support to the conclusion of Fievez, that the effect of a magnetic field is to produce reversals. The appearance of the figure itself seems to indicate a true separation, the depression bearing a much larger proportion to the whole area than we are accustomed to observe in reversals; but this by itself would hardly be considered conclusive. It was thought, however, that if there were a true separation, the distance between the components should vary with the strength of the field, whereas in the case of a reversal one would expect only an increase in the darkness of the absorption.

Accordingly a series of observations was made with varying strength of field, the results of which are shown in the visibility curves of Fig. 1, and the corresponding intensity curves of Fig. 2. The strength of field, in the order of the letters was 0, 5, 7, 11, 16, 20. It appears from the figures that up to a strength of field 11, which is about 2000 C. G. S., the principal effect is a doubling of the line; but beyond this, the component lines are broadened as well as separated. It is also clear that the separation is nearly proportional to the strength of field. Thus, assuming this law to be true, the following table shows the agreement between the observed and the calculated distances.

F = strength of field; Δ = difference of path in millimeters corresponding to visibility 50 for single source; δ = the corresponding half width of the source on a scale of 100 for $D_1 - D_2$; D = the period of the coincidences in millimeters due to the doubling; and a = the corresponding distance between the components.

TABLE I.

	F	Δ	δ	D	a	a calc.
A	0	20	.66	∞	0.0	0.0
B	5	20	.66	58	1.0	1.0
C	7	20	.66	38	1.6	1.5
D	11	20	.66	28	2.2	2.3
E	16	14	.94	18	3.3	3.4
F	20	10	1.32	14	4.3	4.2

[1] A triple line would give a totally different visibility curve.

The next substance examined was cadmium. Cadmium filings were enclosed in an end-on vacuum tube which was placed between the poles of the electro-magnet. The results are

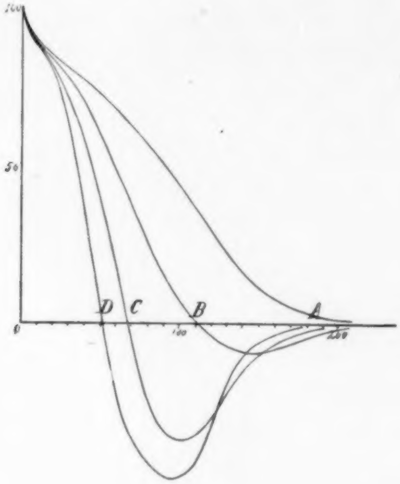


FIG. 3.

shown in Figs. 3 and 4, and prove that there is scarcely any broadening of the red cadmium line with the magnetic fields used. The doubling is even more pronounced than in the case

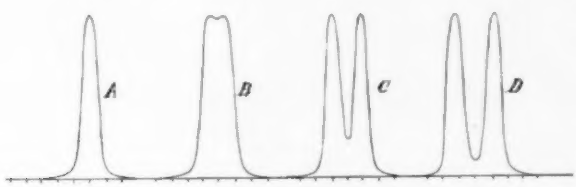


FIG. 4.

of sodium, and the following table (page 52) shows that the distance between the components is proportional to the strength of field.

The results with cadmium are therefore essentially the same as with sodium, and are perhaps even more convincing from the

TABLE II.

	F	Δ	δ	D	α	α calc.
A	0	90	.15	∞	.00	.00
B	4	90	.15	220	.27	.28
C	6	90	.15	136	.44	.42
D	9	90	.15	102	.59	.63

fact that the red cadmium line is almost ideally simple. Further, the fact that the same results are obtained under such very different conditions (metallic cadmium vapor in a vacuum tube

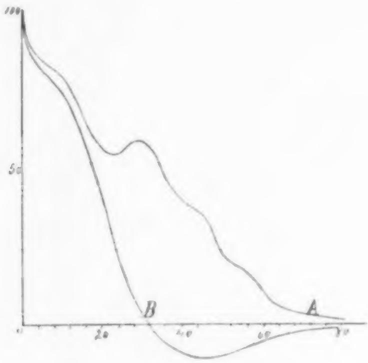


FIG. 5.

as against sodic carbonate in a blowpipe flame) would seem to furnish additional evidence against the reversal hypothesis.

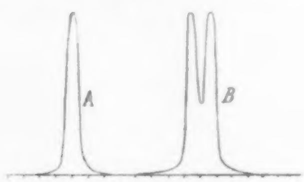


FIG. 6.

The light from sodium in a vacuum tube has a somewhat complicated and variable structure, but in one experiment, the result of which is given in Fig. 5, the visibility curve (envelope)

is relatively simple, and the corresponding intensity curves, Fig. 6, show results almost identical with *A* and *B*, Fig. 2. The strength of the magnetic field was approximately the same in the two cases.

The green cadmium line, however, is both separated and broadened, and the blue line more than the green. The green

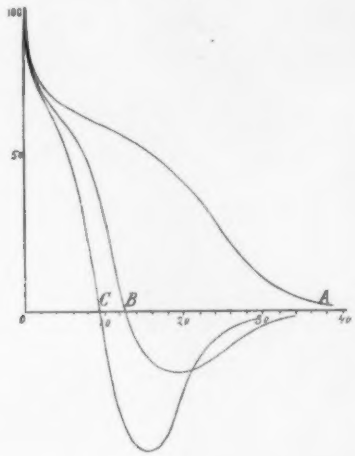


FIG. 7.

line of mercury is rather interesting on account of its complicated structure, and the results show that the general effect of the magnetic field is to obliterate details of structure, changing the form to a simple doublet, as in the other cases. The separation and the broadening are nearly the same as for the green cadmium line.

Hydrogen in a vacuum tube and lithium and thallium in the blowpipe flame are but little affected. These lines are all originally double, and in all three cases the only effect observed in the magnetic field is a slight broadening and a slight increase in the distance between the components.

In all the preceding experiments the light was examined in a direction at right angles with the magnetic field. When sodium light was allowed to pass through cylindrical holes in the pole-

pieces, so that the pencil was parallel with the field, the same effect of separation of the line into two was observed, and was even more clearly marked than in the transverse direction, but the broadening was inappreciable. This appears from an inspection of Figs. 7 and 8.

The fact that broadening occurs only or chiefly when the pencil of light is at right angles with the field, may possibly be

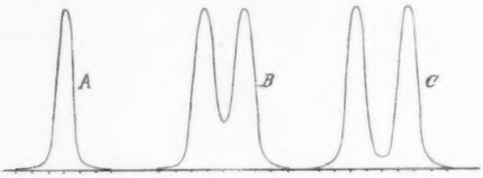


FIG. 8.

accounted for by an increase of velocity of the radiating atom in this direction. This is what should be expected if the atom is electrified and in motion; for then a velocity at right angles with the original one would be added, giving a resultant velocity greater than before. The effect of this increased velocity would be a displacement of the corresponding spectral line proportional to the component of the velocity in the line of sight due to the Doppler effect; and as the increased velocity occurs only in the equatorial plane the broadening would be observed chiefly in this plane.[1]

According to Zeeman the only effect of the magnetic field is to broaden the spectral lines, and the theoretical investigation fails to account for the doubling which has been observed in almost every case thus far examined.

[1] It is worth noting that in almost every instance the magnetic field caused a perceptible increase in brightness.

Minor Contributions and Notes.

ON THE MODE OF PRINTING MAPS OF SPECTRA AND TABLES OF WAVE-LENGTHS.

To the opinions previously expressed in the ASTROPHYSICAL JOURNAL regarding the best mode of printing maps of spectra and tables of wave-lengths, we are now able to add the following statements:

"I see that you invite opinions as to the direction in wave-length of the printing of maps and tables of spectra. I regard the two cases as distinct. I am strongly of opinion that any change in the direction of maps from the classical one, now further sanctioned by Rowland's great solar map, in which the red is opposite the right hand, would be little less than intolerable in practice. I hope that you will regard the question, in respect of maps, as one that cannot be reopened. The case of tables is different. I think that Rowland's tables are in the wrong direction, and that the classical direction of placing the largest wave-lengths at the top of the tables should be adopted. This would agree with Professor Kayser's view."

WILLIAM HUGGINS.

"I notice that you ask for expressions of opinion in regard to the best mode of printing maps of spectra.

"My vote is for the present decision of the ASTROPHYSICAL JOURNAL, placing the origin of wave-lengths on the left, and this for the following reasons:

"1. The diffraction grating is now and will probably continue to be our principal means of studying spectra under high magnification, and while it is of course possible to use a grating either right or left in observing, we should naturally plot our measurements on the wave-length scale, which is the one given by direct observation with a Rowland's apparatus. If we adopt the λ scale, we should also expect to use the common convention of mathematicians in curve-tracing, allowing its positive numerical value to increase on the right hand.

"2. We must lay our plans for probable future growth, and here it seems to me that there is great hope of development in the infra-

red region, which in extent far exceeds all the rest of the spectrum, and which also includes the larger part of the radiant energy in all but the emanations from the hottest sources. Instead of compressing the infra-red into a small space, which must be done if the frequency scale is used, it is desirable to leave room for indefinite extension in this direction.

"3. The sequence of numerical properties in the frequencies of vibration for certain substances might be urged as one reason for adopting a frequency scale, and placing this with its zero on the left, were it not that there are sequences running in either direction, and thus there is no particular reason why we should adopt a different order from that of direct wave-length measurement unless we propose to give up all order, and let each investigator please himself in this matter.

"But (4) if it is a good thing to have an established order, it should be selected on the principle of conducing to the greatest use: and here it seems to me, while admitting the existence of good arguments on the opposite side, the chief use of the order in question is to aid the memory in recalling the disposition of a host of objects. But with this purpose in view it makes less difference what the order is than it does to have it include the chief examples to which we must continually recur. The majority of the most important publications in this line place the violet end of the spectrum on the left. It is therefore well to continue the practice.

"If the question be argued much farther, we shall land in metaphysics; but it might be pointed out that since time is measured by change of position of bodies in space, our foundation should be laid in space (λ) rather than in time $\left(\frac{1}{\lambda}\right)$.

"I prefer the micron as the unit of wave-length since its size is commensurate with the thing to be measured, and it seems to be the natural unit for microscopists. It is time enough to consider millimicrons ($\mu\mu$) when we get to chemical molecules, and the tenth-meter is yet farther away from our object (the measurement of wave-length) involving, in the case of an imperfectly known λ, the addition of one or more insignificant ciphers, which is misleading, or else requiring the adoption of a makeshift such as the colon (:) or dash (—) in place of unknown final figures, as in Frost's Scheiner."

FRANK W. VERY.

NOTE.

As Mr. Jewell's letter in the April number of this JOURNAL might imply to those who have not read Dr. Arendt's article in *Wiedemann's Annalen* that the reviewer of the article had introduced errors into it, the words in question of the reviewer are here repeated, together with the extracts from Dr. Arendt's paper upon which they were based.

This JOURNAL (**5** : 153): "To calculate the corrections it was necessary to test the law of increase of intensity of the lines with increase of path, which from observations of Cornu and of Müller was expected to be that of direct proportionality. This was fully confirmed by series of observations on the same day at different solar altitudes."

Wied. Ann. (**58** : 191): "Aus diesen Angaben lässt sich leicht ein Correctionsglied bestimmen, sofern nur der gesetzmässige Zusammenhang zwischen Weglänge und Stufenwerth der Linien bekannt ist. Nach Cornu und Müller soll die Zunahme der Linienintensität der Vergrösserung des Luftweges direct proportional sein. Bei der Bedeutung, welche dieses Gesetz im vorliegenden Falle besitzt, schien es mir wichtig, dasselbe noch einmal eingehend zu prüfen ; zu dem Zwecke wurde eine Anzahl von Beobachtungsreihen bei dem verschiedensten Sonnenstande mit dem schon früher erwähnten kleineren Spectralapparate ausgeführt."

Page 192 : "In übersichtlicher Weise kann man durch Anwendung des graphischen Verfahrens ein Bild von dem Zusammenhange zwischen Linienintensität und Weglänge gewinnen, indem man in ein rechtwinkliges Liniensystem die vom Lichtstrahle durchlaufenen Wegstrecken in der Luft als Abscissen und die entsprechenden Stufenwerthe der Linien als Ordinaten einträgt; die Verbindungslinie der Endpunkte der letzteren nähert sich einer Geraden." Later (p. 196) Arendt refers to the "in der Tabelle *C* geführten Nachweis von der Proportionalität zwischen Weglänge und Linienintensität."

Of course Mr. Jewell's more detailed reference to his own observations is preferable to the necessarily brief allusion to them in the review, where it was only remarked that "The procedure adopted by Dr. Arendt appears as suitable, and the results obtained as satisfactory as those described by Jewell in a late number of this JOURNAL (**4**, 324–342), where a photographed scale was employed for comparisons of intensity."

EDWIN B. FROST.

DEDICATION OF THE YERKES OBSERVATORY.

THE formal dedication of the Yerkes Observatory will take place on October 1, 1897. Although the details of the programme have not yet been arranged, it is considered desirable to give early announcement of the date. It is hoped that European men of science who purpose to attend the Toronto meeting of the British Association for the Advancement of Science, in August, may think it desirable to take part in the formal inaugaration of the Yerkes Observatory. In connection with the dedicatory exercises it is planned to hold a series of informal conferences on astronomical and astrophysical subjects. The fourth annual meeting of the Board of Editors of the ASTROPHYSICAL JOURNAL will also occur at the same time. A cordial invitation is hereby extended to all men of science who may be willing to honor the Observatory by their presence on this occasion.

GEORGE E. HALE.

ERRATA.

The following corrections should be made in the Rev. J. Fényi's article "Prominences Observed on August 8, 1896" in this JOURNAL, **4**, 263, November 1896.

Page 263, line 9, for $22^h\ 40^m$ read $21^h\ 40^m$.

In the table $+29°$ should be added to the heliographic latitudes of all prominences on the east limb, and $-29°$ to the latitudes of those on the west limb.

For the words *Heliogr. Long.* at the head of the third column of the table substitute *Heliogr. Lat.*

The drawings reproduced in Plates VII and VIII are correct.

RECENT PUBLICATIONS.

A LIST of the titles of recent publications on astrophysical and allied subjects will be printed in each number of the ASTROPHYSICAL JOURNAL. In order that these bibliographies may be as complete as possible, authors are requested to send copies of their papers to both Editors. For convenience of reference, the titles are classified in thirteen sections.

1. THE SUN.

HILLS, E. H. Total Solar Eclipses. M. N. **57,** 282–284, 1897.

MAIER, M. Sonnenbeobachtungen für das Jahr 1896. A. N. **143,** 95, 1897.

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